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Management of Low-Productivity Fisheries:
Collapse and Recovery of Alberta's Walleye (*Sander vitreus*) Fisheries

by

Michael Gary Sullivan ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

Environmental Biology and Ecology

Department of Biological Sciences

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University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Management of low-productivity fisheries: collapse and recovery of Alberta's walleye fisheries* submitted by Michael Gary Sullivan in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Environmental Biology and Ecology.

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Abstract

Collapses of low-productivity, northern fisheries following increases in fishing effort are axiomatic to fishermen, but quantitative evidence is rare because of the large temporal and spatial scales usually required to demonstrate such changes. In Alberta, an unusual combination of persistently high fishing effort, relative to low biological productivity, has resulted in documented declines and collapses of important recreational, commercial, and First Nations subsistence fisheries for walleye *Sander vitreus* (Mitchill). Minor changes to traditional sport fishing regulations (e.g., bag and size limits, and season restrictions) failed both to prevent recruitment overfishing and to allow the recovery of collapsed fisheries. I quantified three proximate, depensatory mechanisms for these failures: inverse relationship of illegal harvest to catch rate, perceived hyperstability in reported fishing quality, and the loss of cultivation effects by walleye on forage fishes. After extensive public consultation, major restrictions were implemented on the recreational harvest, which allowed the recovery of growth-overfished populations. Paradoxically, these recoveries demonstrated the inability of traditional regulations to sustain fisheries under conditions of high fishing effort and low biological productivity. Alberta's case history demonstrates the narrow range of conditions under which traditional regulations are effective in maintaining northern fisheries and illustrates the need for direct harvest controls. In order to overcome strong social constraints to management, stock assessment biologists must provide decision-makers with the full perspective of potential fishery status. This may be achieved by adopting a new model for managing low-productivity fisheries, incorporating both direct and indirect harvest controls.

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Starting a doctoral thesis when you are nearing 40, raising a young family and passionately involved in a consuming career is damned foolish. Completing the thesis eight years later is testament to the trust and help of family, friends, and colleagues.

To my parents: Thanks for logistical support ad nauseum. Tell all the relatives that after a diploma and three degrees, your son has finally finished school.

To Heidi: For your patience and your knowledge, I am humbled and grateful.

To Sierra and Ben: Thanks for the space and quiet. I'll play with you now.

To Hugh Norris: Thank you, for the thousandth time.

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To John Post: Thank you for being a role model.

To Joseph Nelson: Thank you for demonstrating the dignity of science and the joy of fishes.

To Bob Hudson: You teach clear thinking. The recovery of Alberta's walleye fisheries is a direct consequence of your teaching. The fishes and I thank you.

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Introduction

Low-productivity fisheries, such as those found throughout the Canadian North, decline and collapse when faced with heavy fishing pressure. Fish species such as walleye *Sander vitreus*, lake trout *Salvelinus namaycush*, and northern pike *Esox lucius* are slow-growing and long-lived (e.g., maximum ages exceeding 20 years) in boreal climates. Populations of these species cannot sustain harvest rates above 1 kg/ha without major changes in abundance and structure (Colby and Baccante 1996; Gunn and Sein 2000). Angling effort, particularly in small lakes, can exceed 1 angler-trip/ha, and the inevitable overharvest results in declines in fishing quality. Although seldom directly acknowledged by either biologists or anglers, the spatial and temporal patterns of such declines are axiomatic. Fly-in lodges offer the highest-quality fishing. Anglers tolerate difficult access (e.g., rough roads or long hikes) to remote lakes and streams because superior fishing is expected. Recently accessible lakes are highly attractive to anglers because of the perception of great (but ephemeral) fishing. The temporal pattern is evident through old-timers' tales and faded photographs of large catches of big fish, "before the new road went in."

In spite of these widely known patterns of fish declines with increased fishing effort, the vulnerability of these fisheries is rarely acknowledged in studies or implicit in management strategies. Post et al. (2002) show that only 0.3% (13/4904) of papers published in three leading fisheries journals during the 1990s refer to recreational fishery declines. Sport fisheries are generally believed to be self-regulating (Hansen et al. 2000; Radomski et al. 2001): correlated declines in angler effort and fishing quality result in a compensatory response of declining fishing mortality with decreasing stock size. If anglers respond by not abandoning poor fisheries or if they change their behaviour in other ways (e.g., by increasing trip-length or increasing efficiency), however, this compensatory mechanism of self-regulation fails. The behaviour of anglers suggests that they do not perceive fisheries to be self-regulating. For example, during 2002, every fly-in fishing lodge in the Yukon Territory advertised a strict catch-and-release policy, an apparent response by lodge operators to a perceived vulnerability of fish populations at relatively low fishing pressure. Territorial fishing regulations, however, allowed generous daily bag limits (e.g., three lake trout, two bull trout, and five pike/day) at higher-use, road-accessible lakes with low fishing quality. The disparity between these management strategies (i.e., restricting harvest at low-effort, high-quality fisheries and encouraging harvest at high-effort, low-quality fisheries) contradicts the theory of fishery self-regulation. The widespread perception of highest-quality fisheries correlated with lowest access implies a concomitant failure to prevent declines in areas that are easily accessible. This further implies a failure by managers to recognize this effect. It also makes it impossible to inform decision-makers of the present status of fisheries relative to the range of possible stock conditions and of the potential consequences of management actions (or inaction), the express purpose of stock assessment (Hilborn and Walters 1992; Hutchings et al. 1997).

Fisheries managers' lack of acknowledgement of, and response to, fishery declines appears symptomatic of Pauly's shifting baseline syndrome (Pauly 1995; Pitcher 2001). Baseline perceptions of a fishery's status will be those perceived at the beginning of a manager's career, or using the oldest conventional data set. There may, however, not be long-term data sets that show declines in fish populations, or careers that span a long enough time to see the reductions in fish numbers. From one of the longest-running studies of a recreational fishery in North America, Beard et al. (1997) and Newby et al. (2000) concluded that walleye fisheries are self-regulating based on maintenance of the unregulated walleye fishery at Escanaba Lake in northern Wisconsin. Small fish (400 g) and low catch rates (0.1 fish/h), however, suggest that the Escanaba fishery is being maintained at a very low quality when compared to growth-overfished Alberta walleye fisheries (i.e., average weight of fish = 1 kg; catch rate = 1 fish/h). The effects of Pauly's shifting baseline syndrome can be overcome by documenting or experiencing changes over the entire range of population responses (unexploited to collapsed), requiring that these responses be clearly apparent during a relatively short time span. Fisheries studies in low-productivity systems (e.g., boreal, arctic, and alpine) could provide this information, but few scientists study these systems because of expensive access and low political priority. Fish species with low natural productivity in high-productivity areas (and therefore with a greater likelihood of being studied) may have declined in numbers prior to historical implementation of fisheries monitoring (e.g., Atlantic salmon *Salmo salar* in eastern United States, brook trout *Salvelinus fontinalis* in Appalachia, and Arctic grayling *Thymallus arcticus* in midwest United States).

The unusual combination of biological and social conditions that allows the recognition and study of fishery declines has occurred in Alberta. From the 1970s through to the present, a burgeoning petrochemical-based economy and rapidly expanding human population has exerted tremendous pressure on Alberta's low-productivity walleye fisheries. Collapses in major recreational fisheries recently became apparent to both managers and fishermen. My objective was to document the decline and collapse of Alberta's walleye fisheries and describe the dilemmas posed by recovery so that managers may recognize the vulnerability of low-productivity fisheries. Additionally, I investigated the proximate causes and mechanisms of collapse to determine why these fisheries were not self-regulating.

My dissertation is composed of five chapters each prepared as an independent document intended for primary publication. Chapter 1 documents the collapse of Alberta's walleye fisheries and describes the dilemmas presented by the recovery of growth-overfished stocks. The specific depensatory mechanisms of collapse pertaining to anglers' behaviour are described in Chapter 2 (i.e., illegal harvest) and Chapter 3 (i.e., perceived hyperstability). Chapter 4 describes the test of an important technical assumption of the new techniques used in Chapters 2 and 3. In Chapter 5, I investigate a depensatory biological mechanism of fisheries collapse. I conclude my dissertation by discussing why fisheries management in Alberta failed to prevent declines and propose a new model for management of low-productivity fisheries.

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Chapter 1. Active Management of Walleye Fisheries in Alberta: Dilemmas of Managing Recovering Fisheries

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Abstract.—Managers of recreational walleye *Sander vitreus* fisheries in Alberta, Canada, face an unusual combination of very low productivity (related to the northern climate) and high fishing pressure. Passive management of the large recreational fishery and active management of the smaller commercial fishery failed to prevent declines and collapses of walleye stocks. During the 1990s, extensive consultations with the public resulted in the development of an active recreational fishery management system, using set points to classify stocks. Catch-and-release and large, highly restrictive length limits were used to regulate the harvest. These restrictions on the recreational harvest resulted in a dramatic increase in catch rates of growth-overfished stocks. Paradoxically, this recovery has created dilemmas and controversies in both the recreational and commercial fisheries. Anglers are now dissatisfied with low harvest rates and absence of large fish, in conjunction with high catch rates of small fish. The total allowable catch, however, is being taken by hooking mortality and illegal harvest of undersize walleye in the recreational harvest. In commercial gill-net fisheries for lake whitefish *Coregonus clupeaformis*, increasing by-catch of walleye restricts the harvest of lake whitefish and has created uneconomical fisheries. Resolving these dilemmas will require dramatic changes to fisheries management techniques in Alberta.

Introduction

Failure to prevent widespread and long-term declines in recreational fisheries is increasingly being recognized (Knudsen and MacDonald 2000; Schindler 2001). Although declines are well documented in marine and commercial fisheries (Hutchings and Myers 1994; Tough 1999; Musick et al. 2000), declines in freshwater recreational fisheries have only recently become apparent (Post et al. 2002). Some stocks, such as lake trout *Salvelinus namaycush* in northern Ontario, are so vulnerable to rapid overexploitation by anglers that managers may not be aware of the collapse without intensive monitoring (Gunn and Sein 2000). With other stocks, such as bull trout *S. confluentus* in western North America (Mackay et al. 1997; Post and Johnston 2001), declines may occur over many decades and pass relatively unnoticed. Management of these recreational fisheries has traditionally relied on indirect, passive harvest controls such as creel limits and size limits. While effective when fishing pressure and harvest remain below or near sustainable fish production levels, these techniques may fail when harvest far exceeds production.

New active and precautionary management measures have been proposed to address the failures of traditional fisheries management (Ludwig et al. 1993; Myers and Mertz 1998; Richards and Maguire 1998). These management philosophies represent a major shift away from maximizing harvest to maintaining fish stocks at higher and more ecologically and economically functional levels (FAO 1995; Mangel et al. 1995; Alverson 2001).

Such large-scale changes in management philosophy should result in equally large improvements in fish stocks and fisheries regulations. Management of walleye *Sander vitreus* in Alberta provides fisheries managers with good case histories of such changes. Because of relatively high fishing mortality on slow-growing and late-maturing walleye, Alberta's fisheries experience higher stresses than those in many other jurisdictions. Passive, indirect management, primarily using province-wide creel limits, failed to prevent widespread, major declines in walleye fisheries. After considerable debate, a more active management strategy was implemented in 1996. The new strategy involved strong public participation and heavy restrictions on the recreational harvest. The initial dramatic response of growth-overfished stocks of walleye resulted in paradoxical dilemmas created by rapid increases in abundance of fish stocks and demonstrated the inability of traditional management tools to adapt to an unprecedented combination of high catch rates and high fishing pressure on unproductive stocks. My objective is to demonstrate the difficulties of, and offer solutions for, managing collapsed and recovering fisheries.

Study Area

Alberta is a large (661,000 km^2), western Canadian province, extending from 49^0 to 60^0 N. Most of Alberta's walleye fisheries are located in the boreal forest zone (roughly between 54^0 and 60^0 N), which is near the northern edge of the range of walleye (Scott and Crossman 1973). Ice covers lakes from November until May, and air temperatures average $^-2^0$C to 2^0C annually. Winterkill is common in lakes smaller than 200 ha, and many lakes are anoxic below the thermocline. Alberta is unusual in Canada for its lack of lakes. Excepting three small Maritime Provinces, Alberta has the least amount of area covered by fresh water and its boreal lakes (approximately 800 with game fish and only 177 with walleye) have a low diversity of fish species, with no centrarchid and few salmonid fisheries. Walleye, northern pike *Esox lucius*, and yellow perch *Perca flavescens* are generally the only game species found in the popular fishing lakes (Nelson and Paetz 1992). The walleye is one of the most popular game fish species in Alberta and is the primary focus of most angling effort on lakes (Berry 1995a). Excellent descriptions of the fishes and aquatic habitats of Alberta are presented in Nelson and Paetz (1992) and Mitchell and Prepas (1990).

Methods

Fisheries information was compiled from field studies and historical sources. Recreational fisheries and biological data were collected from a series of creel surveys conducted on Alberta lakes from 1983 to 2000. Creel surveys were almost exclusively summer-season, single access-point surveys. Virtually all anglers fished from boats and were interviewed on shore at the completion of each trip. Catch rate (CUE) is the reported catch divided by the reported angling effort. Catch includes both harvested and released walleye, unless otherwise noted. Walleye age was estimated by counting annuli on opercula and on sectioned spines and rays from pelvic fins (Mackay et al. 1990). Age estimates were validated by following year-classes of unusual strength and by sampling walleye of known age in stocked populations. State of sexual maturity of walleye was determined following Olynyk (1985). Test angling was used to collect data on size-classes of walleye typically released by anglers. Anglers of various skill levels test angled throughout the summer season, using a variety of gear types. Length (to the nearest mm of fork length, FL or total length, TL) of all walleye caught by test angling was measured and a fin spine was removed for age estimation. Growing degree-days (GDD5^0C) (the annual sum of mean daily temperatures greater than 5^0C) were obtained as Canadian Climate Normal values for 1971–2000 from the Meteorological Service of Canada, Environment Canada. Commercial fishing data from 1942 to 1975 were obtained from Scott (1978). More recent commercial fishing records are from unpublished data, as are records of First Nations fishing activities. Anecdotal, historical (prior to 1976) information was derived from local environmental knowledge surveys, which included interviews conducted in 1996 and reports from public archives (Valastin and Sullivan 1997). Geographical, limnological, and fisheries data from lakes discussed in this paper are presented in Appendix 1.

Results

Biological Productivity

The cold climate of Alberta results in fish that grow slower and mature later than those in southern jurisdictions (Figure 1). A preferred-size walleye (510 mm TL) in Alberta is typically 8–12 years old and memorable-size fish (630 mm TL) often exceed 15 years old.

Growing degree-days in the geographical area containing most walleye lakes range from 900 to 1400, so walleye mature at older ages than in fisheries with slightly higher GDD5^0C values (Figure 2). In low-density, heavily exploited populations, females may be fully mature as young as 7 years of age, whereas in high-density, lightly exploited populations, females may be fully mature as old as 20 years of age (Figure 3).

Late maturity and slow growth results in low productivity fisheries that can only sustain low annual total allowable catches (TAC). Based on Colby and Baccante (1996) and long-term commercial harvest data, the estimated TAC for healthy Alberta walleye fisheries is seldom higher than 1 kg/ha. Over-fished stocks would have a much lower TAC, with annual yields of less than 0.3 kg/ha.

Fishing Pressure

Anglers, commercial fishermen, First Nations subsistence fishermen, and commercial poachers exploit most walleye populations in Alberta. Alberta's human population is growing rapidly, increasing from less than one million people in 1950, to two million in 1980, and over three million in 2000, primarily as a result of an expanding oil and gas industry. Rapid human population growth raises the potential for future large increases in numbers of fishermen, as well as increased access to previously remote areas of Alberta.

Prior to the 1990s, management of recreational walleye fisheries in Alberta relied primarily on passive, indirect management techniques, including province-wide creel limits and open-access licensing. Angler numbers increased rapidly, from 122,000 in 1965, to 245,000 in 1975, and 343,000 in 1985, but declined during the 1990s to a low of 212,000 in 1999. Angler numbers increased slightly during the past three years (2000–2002). Compared to the many thousands of lakes in Saskatchewan, Manitoba, and Ontario, Alberta has few lakes (approximately 800 with game fish) and a large number of licensed anglers, thereby resulting in an extremely disproportionate ratio of anglers to lakes (Table 1). Summer-season angling effort at individual lakes can be high relative to the low biological productivity and averaged 9.6 h/ha during the 1980s and 1990s.

Prior to the 1980s, open-access commercial fisheries (primarily winter gill-net fisheries) operated on most of Alberta's walleye lakes. Commercial fisheries often targeted walleye or caught heavy by-catches of young walleye in small-mesh gill-net fisheries meant to catch lake herring *Coregonus artedi*. Since the 1980s, commercial fisheries have been increasingly regulated to target only lake whitefish. Presently, managers use by-catch quotas, and restrictions on mesh size, areas fished, and seasons to minimize by-catch of walleye. Increased regulations, low fish prices, and cessation of open-access licensing reduced participation in this relatively small industry (average annual value of Can$2.9 million, 1996–2000). About 800 commercial fishermen are licensed annually, with fisheries on about 130 lakes. Although small when compared to the recreational fishery (more than 250,000 anglers; estimated annual economic activity in excess of $340 million in 1994, Berry 1995b), commercial fishing associations are politically astute and are major forces affecting fisheries management in Alberta. During the 1980s, commercial fisheries harvested only one walleye for every six walleye harvested by recreational fisheries.

The First Nations fishery is exclusively a gill-net fishery for subsistence and is regulated to target lake whitefish through restrictions on net size and mesh size, areas fished, and seasons. Based on the low number of licenses, gear restrictions, and economic limitations (sales of fish are illegal), this poorly documented fishery likely harvests relatively few walleye.

At a few lakes in Alberta, undercover enforcement officers documented that illegal commercial poachers (typically gill-netting walleye for sale to restaurants) take considerable numbers of walleye. However, commercial poaching is likely confined to lakes with high walleye catch rates.

Fisheries Decline

Prior to the 1990s, relatively unrestricted recreational and commercial fishing pressure caused the decline of many walleye populations to a small fraction of their former abundance. Commercial catches of walleye at several of Alberta's largest and most economically important lakes had virtually disappeared by the 1980s (Figure 4). Anglers reported numerous walleye population collapses and complained of mismanagement (Chipeniuk 1975). A survey of the historical status of Alberta's walleye fisheries identified 27 lakes ranging from "good to excellent" prior to 1976 (Valastin and Sullivan 1997). By 1998, 12 of these were classified as having collapsed, 13 were vulnerable, and only 2 were stable (1998 Alberta Guide to Sportfishing Regulations).

Some walleye fisheries in Alberta have declined to extremely low levels (Table 2). One of these, at Lac La Biche, was once one of Alberta's largest walleye fisheries. References dating back to the 1890s described the superlative fishery at Lac La Biche (Belanger 1895). Local fishermen described the walleye fishery using terms such as "exceedingly abundant," "thick with walleye," "abounds," "wall-to-wall," and "exceptionally good." A tourism film was produced that highlighted the "astounding catches" of walleye by anglers at Lac La Biche (Hutchinson and Ross 1955). By the 1970s, this fishery had collapsed and has not yet recovered (Figure 5).

One extensively studied fishery demonstrates the large increase in angling effort and a concomitant precipitous decline in walleye abundance. During the 1970s and 1980s, Wolf Lake (3,150 ha) was a popular walleye fishery in northern Alberta, with only one boat launch and a primitive campground (i.e., no cottages, marinas, stores, or serviced developments). The only access to this lake was via a single gravel road. In 1979, angling effort was estimated to be less than 2000 angler-days, but by 1994, angling effort increased to more than 10,000 angler-days. During this period, the harvest rate of walleye dropped by 95%; from 0.21 to 0.01 walleye/h. Yield from the summer recreational fishery averaged 0.30 kg/ha (range = 0.05–0.49 kg/ha), with the smaller commercial fishery taking an additional 0.16 kg/ha (range = 0.05–0.32 kg/ha). In 1991, a mark-recapture survey at Wolf Lake suggested that the density of walleye was near 1 adult/ha (Barton 1991), which was far below the 25% quartile (7.8 adult walleye/ha) of densities of North American walleye populations (Baccante and Colby 1996). With the collapse of the walleye fishery, anglers began abandoning Wolf Lake (Figure 6). Changes in walleye age-class distribution illustrated a progression from growth overfishing (Cushing 1981) to recruitment overfishing (Figure 7).

Although most anglers readily blame commercial fishermen for declines in walleye populations, overharvesting by recreational fishermen appears to be a major cause of declines in Alberta. Walleye fishery collapses occurred at several lakes with rare, intermittent commercial fisheries and easily accessible, recreational fisheries (e.g., Floatingstone, Garner, Gregoire, Moore, and Shiningbank lakes, Appendix 1). Anglers successfully caught walleye at two restricted-access (i.e., low angling effort) walleye lakes in a military reserve in northern Alberta, compared to nearby easily accessible (i.e., high angling effort) lakes outside the reserve, in spite of both groups of lakes being extensively gillnetted (Table 3). The importance of angling overharvest in causing walleye fishery declines is suggested by rapid recovery of walleye stocks at lakes with restricted angling harvest, but continued gill-net harvests (e.g., Beaver, Iosegun, Moose, and Lesser Slave lakes).

Development of Active Management

Managers and the public gradually recognized the decline and collapse of walleye fisheries in Alberta, even without a provincial fisheries monitoring strategy. From the mid-1980s to 1994, a series of in-house walleye management committees were formed, but failed to reach consensus on data interpretation and management strategies. During this time, managers implemented various regulations, including small length limits (province-wide), spawning season and area closures (sporadic), slot-length limits (4 lakes), and catch-and-release regulations (2 lakes), but had few defined, quantified management goals.

In 1994, a new decision-making strategy was adopted. Public acceptance of any new management strategy was believed to be crucial, both for political and bureaucratic acceptance of the regulations and for compliance with the new laws. To gain this acceptance, the public was asked to design new regulations. To this end, 17 town-hall-style meetings were held throughout Alberta (from November 1994 to February 1995). High-profile local persons associated with walleye fisheries were invited and were given detailed information about the design of a new walleye management strategy. At these meetings, information about the biology of Alberta walleye and how heavy fishing pressure had affected their populations was presented. Walleye stocks were classified into four categories (collapsed, vulnerable, stable, and old-growth). Instead of designing regulations for specific lakes, participants were asked to draft them for each category of walleye fishery. When fisheries at specific lakes were discussed, little consensus could be reached on appropriate regulations. When the generalized categories were discussed, however, participants were much more likely to agree on common strategies. The design of the regulations was based partly on computer simulations and simple fishing regulation games, and partly on discussions within the groups. Each group proposed similar regulations, probably because of the limited combination of creel limits and size limits that demonstrated could effectively reduce the harvest of these fisheries.

The active management system follows a three-step iterative cycle: stock status, harvest policy, and regulation. The cycle was initiated by classifying the status of a walleye stock using biological and fisheries parameters as set points (Table 4). Based on this classification, pre-determined harvest policies and angling regulations were implemented (Table 5). A change in stock status (i.e., denoting the success or failure of the regulation) reinitiates the cycle. This system implicitly provides managers with well-defined, quantified goals for each walleye fishery and allows the success or failure of management actions (typically recreational fisheries regulations) to be readily assessed.

The province-wide, active management system was implemented during the 1996 angling season. By 2000, all of Alberta's lake walleye fisheries had been classified and 80% (142 of 177) of them were rated as either collapsed or vulnerable. Many of these fisheries were classified, however, without the benefit of recent data. In northeastern Alberta, an extensive survey during 1996–2000 of the active management program was used to classify 29 walleye fisheries, of which 23 (79%) were listed as being collapsed and 6 (21%) were listed as being vulnerable. None of the recently surveyed walleye fisheries were classified as being stable or old growth.

Response of Walleye Fisheries

The regulations, as expected, resulted in major changes in the harvest of walleye (Table 6). Prior to the imposition of large length limits, anglers released 23% of their catch of walleye. After the restrictions, release rates increased to over 90%. Yields declined by a smaller amount because of concurrent changes in catch rates and effort.

At 13 fisheries with creel survey data from the passive management period (prior to 1989), catch rates increased in seven lakes after 2–4 years of active management (data from 1998–2000, Figure 8). At these fisheries, the mean catch rate increased five-fold, from 0.22 to 1.12 walleye/h. Compared to the mean catch rate at accessible walleye lakes in Alberta prior to 1989, this is more than a ten-fold increase. These recovering walleye populations must have produced abundant young walleye prior to the implementation of restrictive regulations and were therefore growth overfished. At the six other fisheries, mean catch rates remained low (0.12 walleye/h prior to 1989 compared to 0.13 walleye/h in 1998–2000), which suggests that these fisheries were recruitment overfished.

Although catch rates were high in the seven recovering fisheries, the harvest rate was low (mean harvest rate = 0.08 walleye/h, range = 0.01–0.20) because of large length limits. Abundant fish below and few fish above the minimum length limits typically define the length distribution of walleye caught from these recovering fisheries. At three lakes, length distributions of walleye did not improve during the period of length restrictions. Abundance of larger walleye increased at Pinehurst Lake during years of length restrictions, but not at Baptiste or Beaver lakes (Figure 9). At all seven recovering fisheries, few harvestable-length walleye and virtually no preferred-, memorable-, or trophy-length fish were present. All seven fisheries are still classified as being vulnerable.

Anglers are neither consistently abandoning nor concentrating on these recovering fisheries, in spite of restrictions, low harvest rates, and small walleye. At the seven recovering lakes, angling effort declined at five lakes and increased at two lakes, compared to angling effort measured during the 1980s. The average angling effort at these lakes (7.4 h/ha) was slightly lower than the provincial average (9.6 h/ha).

The Dilemma of Recreational Fisheries

The initial response of Alberta's walleye fisheries to restrictive regulations has presented fisheries managers with a difficult and novel set of conditions. We are still faced with heavy fishing pressure on unproductive fish stocks, but this now occurs in combination with high catch rates. Anglers are dissatisfied with low harvest rates and catching only small fish. Because of the apparent dramatic recovery of walleye stocks, anglers are lobbying managers to increase harvest. No additional harvest, however, can be supported. Increased catch rates cause angling harvest, and incidental mortality of anglers' catch of undersize walleye, to account for the entire allowable harvest.

Hooking mortality of released walleye can be low if release is immediate (0% to 3%), but is higher if release is delayed (Armstrong 1995). Enforcement officers in Alberta report that anglers commonly delay releasing their walleye in the hopes of upgrading to a larger fish. In a study of seven Alberta lakes with high catch rates, anglers keeping walleye illegally killed at least 2.4% (range = 0.2–5.5) of undersize walleye they caught (Sullivan 2002). Erring on the conservative side, estimated hooking mortality was 5% and estimated illegal harvest was 5% at Alberta's recovering walleye fisheries. Combined mortality was thereby estimated to be approximately 10% for undersize walleye caught by anglers.

The estimated kill of undersize walleye at the seven recovering fisheries surveyed during 1998–2000 averaged 44% (range = 27–79) of the summer angling yield of walleye. Prior to length restrictions, the estimated kill of released walleye at the same lakes averaged less than 1% (range = 0.2–1.6). Including deaths caused by hooking mortality and illegal harvest, recent angling yield (mean = 0.6 kg/ha, range = 0.4–0.7) is approaching yield measured prior to angling restrictions (mean = 0.7 kg/ha, range = 0.2–1.6), and is probably near TAC for these recovering, but still vulnerable stocks. In addition, commercial and First Nations fishermen harvest fish from these stocks.

A simple linear model, using catch rates of 1–2 walleye/h and a combined hooking and illegal mortality rate of 10%, shows that the kill of undersize walleye alone would exceed the annual TAC for stable walleye stocks from lakes with angling effort of 11–21 h/ha (Figure 10). This level of angling effort is well within the range estimated for Alberta walleye fisheries (mean = 9.6 h/ha, range = 0.3–74.6 h/ha, n = 78 lakes). Although this angling effort may appear low to managers in southern (and more productive) jurisdictions, similar angling effort resulted in rapid declines in the quality of walleye fishing at lakes in northern Ontario (Baccante and Colby 1991).

The Dilemma of Commercial Fisheries

Commercial fishermen often cannot meet their lake whitefish quota because the by-catch quota of walleye is quickly exceeded, and the commercial fishery is, therefore, immediately closed. The resulting short season (usually lasting only one day) create derby-style races for fish and problems with by-catch, similar to those described for Alaska's marine fisheries (Crowder and Murawski 1998). Managers have little or no opportunity to change fishing zones or strategies during a season to reduce by-catch. Derby-style fisheries create conflicts among commercial and recreational fishermen, and fisheries managers.

The lost value of foregone catch (the difference between the quota and the harvest) of lake whitefish can be substantial. For example, Pigeon Lake supports Alberta's largest commercial lake whitefish fishery (based on participation). Increasing by-catch of walleye over the past five years resulted in rapidly escalating foregone catches and declining profits (Figure 11). During 2000, commercial fishermen realized only $46,000 from a whitefish fishery potentially worth $182,000. At several Alberta lakes, the recovery of walleye stocks has led to increased by-catches, early season closures, and high foregone catches, which in turn has resulted in uneconomical commercial fisheries. Disgruntled commercial fishermen are demanding compensation and higher by-catch quotas.

Higher by-catches, however, are strongly opposed by anglers. Prior to 1996, anglers harvested an average of six walleye for every walleye harvested by commercial fishermen. When active management was implemented and length limits restricted angling harvest, this ratio immediately changed, although the total harvest declined (Figure 12). Dissatisfied anglers now see commercial fishermen taking nearly half of the total walleye harvest, and potentially, a larger portion than anglers harvest legally. Anglers are demanding a reduction in commercial by-catch, while commercial fishermen are demanding an increase.

Discussion

Alberta's walleye fishery problem is simple. Anglers can catch 10 walleye per hectare. The TAC is one walleye per hectare. Add to this an unselective commercial fishery, an unknown harvest by First Nations people, and a rapidly expanding human population, and simple solutions are not readily apparent.

Work on walleye in Wisconsin (Beard et al. 1997; Newby et al. 2000) has suggested that walleye angling fisheries can be self-limiting. The primary reason for this is that walleye catchability does not increase with decreasing density (Hansen et al. 2000). As numbers of walleye decline, catch rates and, therefore, harvests also decline. In this situation, passive management tools, such as creel limits, length limits, and seasons, could be effective. Angling effort may also decline as catch rates fall and fishing restrictions increase, decreasing the attractiveness of the fishery (Beard et al. in press). This would allow quick recovery of the walleye stock prior to another cycle of mild overfishing, abandonment, and recovery.

The highly stressed walleye fisheries in Alberta, however, do not follow this self-regulating pattern. Anglers do not quickly abandon fisheries, but rather, continue to exploit walleye until stocks reach low levels. This may be a consequence of Alberta's low game fish diversity and lack of alternate fisheries, similar to the situation leading to the decline of rainbow trout *Oncorhynchus mykiss* fisheries in southern British Columbia (Walters and Cox 1999). Angler effort remains high because the relative attractiveness of the fishery has not changed (Beard et al. in press). Anglers have nowhere else to go, or other species to target, and consequently, they continue fishing despite having little chance of success. As fish populations decline, depensatory responses, including inverse density-dependent catchability (Shuter et al. 1998), illegal harvest (Sullivan 2002), and loss of cultivation effects (Walters and Kitchell 2001), amplify the effects of overfishing (Post et al. 2002). Passive management fails under these conditions.

Implementation of Alberta's active management strategy using large, highly restrictive length limits increased walleye catch rates at accessible, popular fisheries to levels previously measured only at remote, restricted-access lakes. Colby et al. (1994) recommended that specific management plans for recovered stocks be put in place prior to recovery. This assumes, however, that managers have accurate and widely accepted information about conditions of the recovered fisheries. In Alberta, dilemmas created by unexpectedly high catch rates were anticipated by only a few managers, based primarily on computer modeling, but this information was not widely accepted, perhaps because of a distrust of computer models and because of managers' inexperience with such different fisheries conditions. Many believed commercial by-catches would remain low because of previously successful techniques using closed areas, mesh-size restrictions, and seasons. By-catches may have been low because few walleye were present in lakes. Some managers in Alberta believed hooking mortality and illegal harvest were minor influences (Armstrong 1995; Paragamian 1984). However, when combined with Alberta's high catch rates, small rates of hooking mortality and illegal harvest now claim the entire TAC. Anglers dissatisfied with heavy by-catch are demanding more harvest, in spite of this being counterproductive to the goal of reducing overall fishing mortality. Similarly, at Mille Lacs Lake in Minnesota during 2002, a high catch-rate fishery for walleye attracted numerous anglers.

A restrictive slot-length limit was implemented to maintain the kill within acceptable levels, but high catch rates and heavy fishing pressure resulted in an estimated post-release walleye kill larger than both the angler harvest and the First Nations allocation. In response, anglers want increased harvest, First Nations are demanding reduced recreational fishing pressure, and fisheries managers need to maintain the kill within negotiated limits (Radomski, in press; R. Bruesewitz, MN DNR, 1837 Treaty biologist, Aitkin, personal communication). As Walters and Holling (1990) and Lester et al. (in press) advocate, the only effective way to demonstrate the scale of these changes is to implement regulations and monitor the outcome. We were optimistic about recovery of Alberta walleye fisheries, but many failed to anticipate the magnitude of the ensuing problems.

At present, our management tools (creel limits and length limits in angling fisheries and by-catch restrictions on gill-net fisheries) are ineffective in resolving the problems of hooking mortality and illegal harvest in the angling fishery and foregone commercial catches. Different strategies and tools must be adopted.

For angling fisheries, lake-specific harvest quotas and limits on numbers of released walleye constitute a possible solution, as attempted at several lakes in Minnesota (Radomski, in press). When the quota is taken, the lake is closed. In mixed-species fisheries, however, this would result in the same problem we now face with our commercial fisheries, where incidental by-catch of the most vulnerable species controls the entire fishery. This results in underharvest of other species and is viewed by anglers and managers as unethical or controversial. As Radomski (in press) describes, the difficulties and expense of enforcing and managing such a system would be prohibitive to management agencies, and the complexity would be unacceptable to anglers (Lester et al. in press).

Another solution involves directly controlling angling effort on individual lakes. This could be accomplished by issuing a limited number of licenses (valid for a specific number of days). The allowable amount of effort could be determined from catch rates (including both harvest and incidental mortality) and the TAC. While being biologically effective, proposals to restrict open-access fishing in Alberta have been rejected by angler groups. For example, a test of limited-entry fishing planned for a single Alberta lake during 2000 was cancelled because of social pressure.

An alternative to limited-entry is limited-harvest angling. Access would remain open to all anglers for catch-and-release fishing, but a restricted number of harvest tags would be issued (e.g., using a lottery-style system already familiar to Alberta hunters). This technique regulates harvest only if angling effort and angling by-catch (i.e., post-release mortality and illegal harvest) remain within acceptable limits. At Alberta lakes, the initial response to total catch-and-release regulations was a major decrease in angling effort. As fishing quality improved, however, some catch-and-release walleye fisheries again attracted large numbers of anglers, with an associated increase in by-catch. With limited-harvest regulations, managers could vary the number of harvest tags issued based on changes in angling effort and estimated by-catch. Limited-harvest regulations were recently proposed in Alberta for one recovering walleye fishery (Pigeon Lake) that is managed by catch-and-release regulations. However, the local fisheries advisory committee opposed the proposal. The advisory committee argued that Alberta had liberal walleye harvest regulations when fishing quality was poor, so now that fishing quality has improved, regulations should be more liberal, not more restrictive (Vance Buchwald, Alberta Fish and Wildlife Division, Red Deer, personal communication). Anglers perceive the poor fishing of past decades as being normal and view recent high-quality fishing as a fleeting opportunity to be quickly exploited, clearly illustrating the effects of Pauly's Rachet in shifting perceptions (Pauly 1995; Pitcher 2001). As Beard et al. (in press) propose, high-quality fisheries will be very attractive to anglers and will need stringent regulations for stock protection. In Alberta's situation, the necessary stringent regulations must be those that control angler effort, but as Hilborn and Walters (1992) state, "The hardest thing to do in fisheries management is reduce fishing pressure."

For commercial fisheries, changing from gill nets to trap nets would allow lake whitefish to be harvested and walleye and other game fishes to be released alive. However, commercial fishing organizations in Alberta strongly oppose this change, because of high cost of traps, initial loss of efficiency as a new technique is developed, and lost costs of gill nets and associated gear. At several lakes, experimental fisheries using trap nets have been attempted. Although trap nets reduced by-catch, fishing associations ostracized commercial fishermen who tried trap nets. Some fish processing facilities in Alberta have refused to accept fish from trap-net fisheries, citing economic inefficiencies. These facilities are presently designed and managed to process large volumes of fish over short periods from intensive derby-style fisheries and claim to be unable to handle small volumes of fish over longer periods from trap-net fisheries. Participation in experimental trap-net commercial fisheries was declining in 2001 when, reacting to pressure from a commercial fishermen's association, the government implemented a moratorium on trap-net fisheries.

Each of the aforementioned solutions to Alberta's fisheries dilemmas are biologically feasible, but have failed because of social, economic, bureaucratic, or enforcement reasons. This illustrates the principle stated by Ludwig et al. (1993): "Rely on scientists to recognize problems, but not to remedy them." Leaders in our profession commonly preach the benefits and necessities of reaching outside of our field for collaboration in attempting to solve problems and in educating others (Knuth et al. 1999; Burger 2000; Knudsen and MacDonald 2000). The example of Alberta's walleye fisheries provides a clear demonstration of the value of these goals. As biologists, we can explain the nature of problems and the potential consequences of actions designed to solve those problems. In this way, we may educate other participants and allow difficult solutions to be more easily adopted.

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Table 1. Licensed resident anglers per lake in four Canadian provinces. Data from provincial tourism bureaus for mid-1990s.

Province	Number of lakes	Number of licenced anglers	Anglers / lake
Alberta	800	250,000	312.5
Saskatchewan	94,000	184,000	2.0
Manitoba	110,000	198,000	1.8
Ontario	250,000	585,000	2.3

Table 2. Lakes with severe declines of walleye in Alberta. Commercial and historical records are from Alberta Natural Resources Service (unpublished data).

Lake	Area (ha)	Historical records and comments on walleye fisheries	Year of Creel Survey	Angling CUE (walleye/h)	Comments
Floatingstone	590	Popular angling fishery prior to 1990s Angling fishery harvested >3,000 walleye in 1985	1997	0.01	Number of anglers declined by 92% (1985–1997)
La Biche	23,400	One of largest walleye fisheries in province Commercial catches exceeded 58,000 kg in 1946	1998	0	Commercial walleye catch = 0 in 1987 (399,000 kg of other species)
Wabamun	7,800	Sporadic catches up to 1942			No commercial catches since 1942
Ste. Anne	4,980	Very popular angling fishery prior to 1990s Commercial harvests up to 14,000 kg in 1963	1997	0.01	Commercial walleye catch = 0 in 1999 (31,000 kg of other species)
Skeleton	790	Locally popular angling fishery prior to 1950s Commercial catches up to 500 kg prior to 1960	1985	0	

Moore	930	Walleye abundant prior to 1950s "Netted 1000 lbs. of walleye each day for 10 days."	1986	0.01	
Muriel	6,320	Sporadic commercial catches (636 kg in 1945)	1986	0	
Garner	620	Locally popular walleye angling fishery prior to 1980s	1996	0	
Wolf	3,150	Excellent walleye angling fishery prior to 1980s	1994	0.01	
North Buck	1,900	Periodically good walleye angling fishery prior to 1960s Commercial harvest up to 1,000 kg in 1954	1998	0	No commercial catches since 1969

Table 3. Angler success in catching walleye, summer-season angling effort, and annual commercial gill-net yields at lakes ($N = 2$) within a military reserve with restricted access angling, compared to adjacent lakes ($N = 12$) with unrestricted access angling in Alberta. Data from on-site angler surveys (1984-1988) and commercial fisheries monitoring (1987) at restricted access lakes (Primrose and Spencer lakes) and unrestricted access lakes (Amisk, Cold, Ethel, Frenchman, Ironwood, Kehiwin, Moose, Muriel, North Buck, Skeleton, Touchwood, and Wolf lakes). All lakes are within 90 km of the military reserve.

	Restricted access lakes		Unrestricted access lakes		
	Mean	Range	Mean	95% C.I.	Range
Angler success (%)	82.8	75.6–89.9	5.6	3.4	0–16.5
Angling effort (h/ha)	1.0	0.1–1.8	9.3	3.8	1.4–20.2
Gill-net yield (kg/ha)					
Walleye	0.4	0.2–0.5	0.1	0.1	0–0.7
Whitefish	5.2	3.7–6.7	4.2	2	1.3–13.7
Pike	0.5	0.4–0.5	0.3	0.2	0.1–1.3
Total	6.0	4.7–7.2	5.0	2.1	1.6–14.4

Table 4. Biological and fisheries parameters used as set points for classifying walleye stocks in Alberta.

	Category of walleye stock			
Parameter	Collapsed	Vulnerable	Stable	Old-growth
Age-class distribution	Narrow	Narrow, 1–3 age-classes	Wide, > 8 age-classes	Wide, > 8 age-classes
Mean age	6–10 years	4–6 years	6–9 years	> 9 years
Age-class stability	No strong year-classes	1–3 year-classes support fishery	2–3 classes with large variance in recruitment	1–2 classes with large variance in recruitment
Length-at-age	50 cm in 4–7 years	50 cm in 7–9 years	50 cm in 9–12 years	50 cm in 12–15 years
Age-at-maturity (years)	Females: 4–7 Males: 3–6	Females: 7–8 Males: 5–7	Females: 8–10 Males: 7–9	Females: 10–20 Males: 10–16
Angling CUE (walleyes/h)	< 0.1	0.5–1.0	1.0–2.0	> 2.0

Table 5. Categories, stock status, harvest policy, and angling regulations for walleye fisheries in Alberta. Length limits are in total length.

Category	Status of stock	Harvest policy	Angling regulation
Collapsed	Late-recruitment overfishing	No direct harvest	Catch-and-release
Vulnerable	Early-recruitment overfishing	Low harvest	50 cm minimum length
Stable	Growth overfishing	Moderate harvest	43 cm minimum length
Old-growth	Lightly exploited	Low harvest	Site-specific

Table 6. Walleye released, yield, CUE, and effort in angling fisheries in Alberta before (pre-1989) and after (post-1996) implementation of active management with restrictive length limits. Regulations prior to 1989 were bag limits of 3–5 walleye/day. Regulations after 1996 were 43 cm and 50 cm minimum length limits at stable and vulnerable lakes, and catch-and-release at collapsed lakes. Data are from summer-season angling fisheries. Yield does not include estimates of hooking mortality or illegal harvest. Values are means with ranges in parentheses.

Category	Lakes (n)	Walleye released (%)	Yield (kg/ha)	CUE (walleye/h)	Angling effort (h/ha)
Pre-1989					
All lakes	26	23 (0–95)	0.49 (0–2.70)	0.11 (0–0.33)	13.0 (1.5–74.6)
Post-1996					
Stable	5	90 (87–96)	0.45 (0.11–0.77)	1.18 (0.43–2.10)	4.5 (1.3–6.9)
Vulnerable	14	92 (76–99)	0.28 (0.03–1.95)	0.43 (0.04–0.89)	9.2 (1.0–37.7)
Collapsed	14	100	0	0.05 (0–0.30)	8.6 (0.3–43.4)

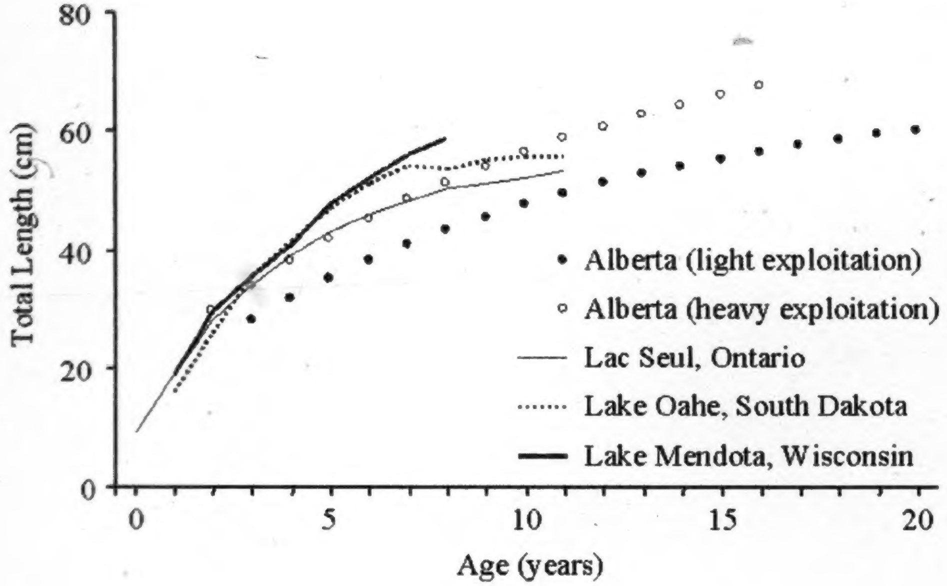

Figure 1. Growth of walleye from six lightly exploited walleye fisheries (Athabasca, Bistcho, Leland, Net, North Wabasca, and Release lakes, 1988–1996: $k = 0.10$, $t_0 = ^-2.7$, $L_{inf} = 677$ mm TL) and six heavily exploited fisheries (Amisk, Touchwood, Gregoire, Hilda, Baptiste, and Moose lakes, 1986–1986: $k = 0.09$, $t_0 = ^-3.10$, $L_{inf} = 837$ mm TL) in Alberta, compared to other fisheries from Ball (1999). Von Bertalanffy parameters were estimated from Slipke and Maceina (2000).

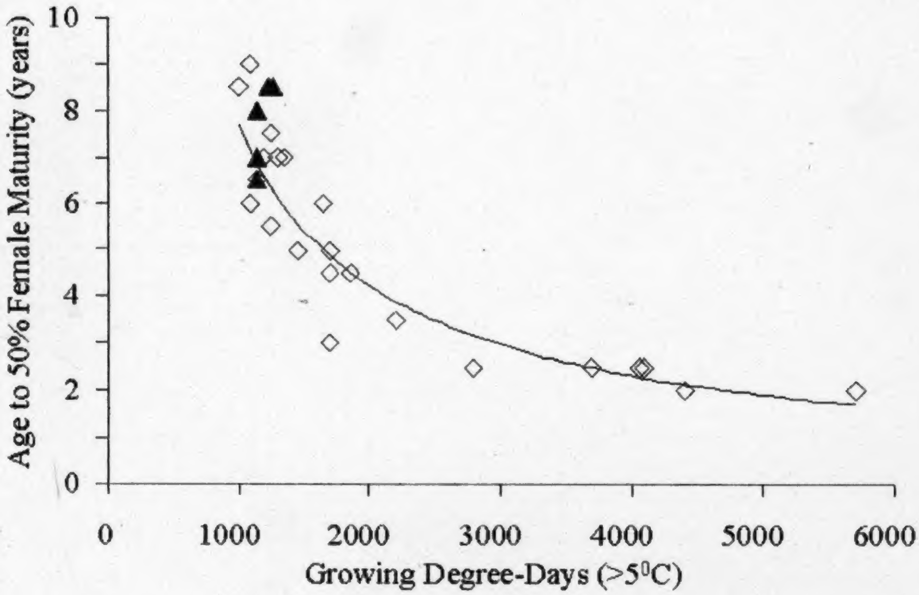

Figure 2. Relationship between growing degree-days (GDD5^{0}C) and age to 50% maturity of female walleye for six exploited walleye fisheries (Baptiste, Lesser Slave, Moose, Pinehurst, Seibert and Touchwood lakes, 1992–1997; solid triangles) in Alberta and for lakes from Baccante and Colby (1996; $y = 3184.72x^{-0.871}$; hollow diamonds).

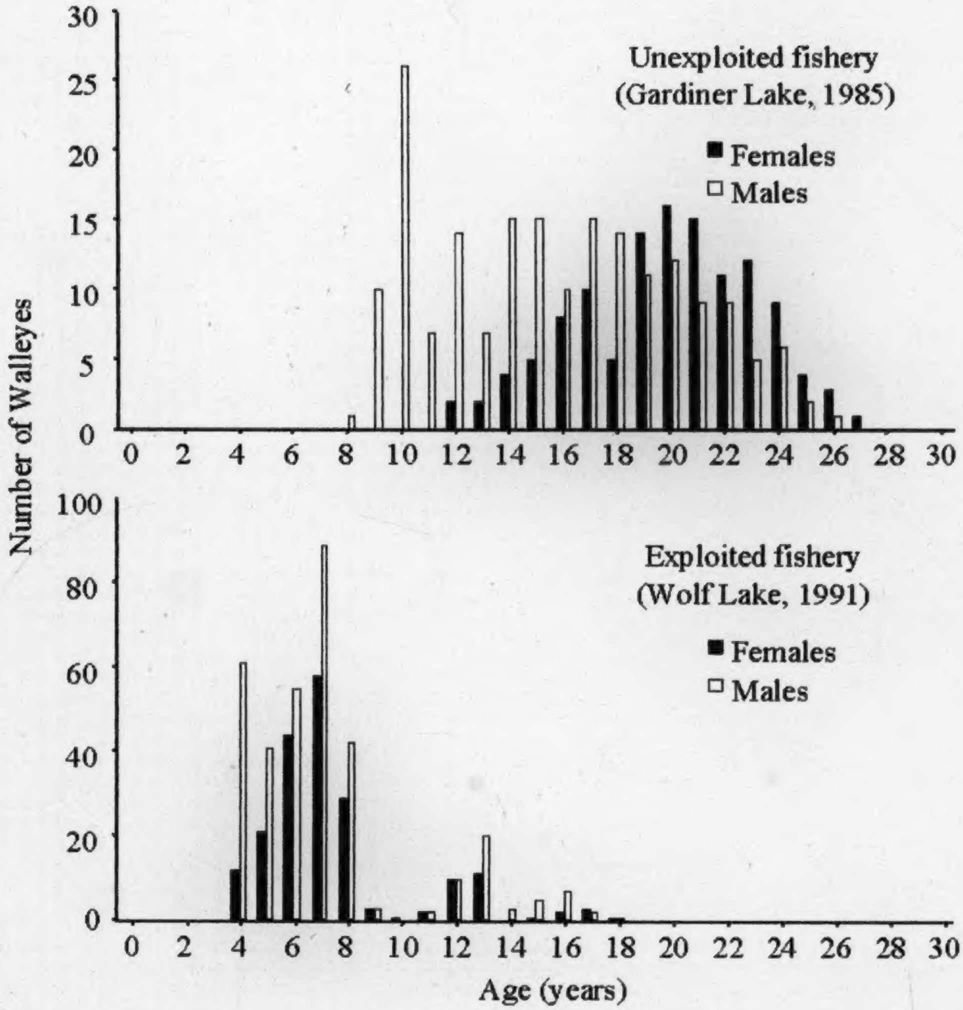

Figure 3. Age distributions of mature walleye, derived from annuli on sectioned fin spines and rays, caught by angling from unexploited (Gardiner Lake, 1985) and heavily exploited (Wolf Lake, 1991) lakes in Alberta.

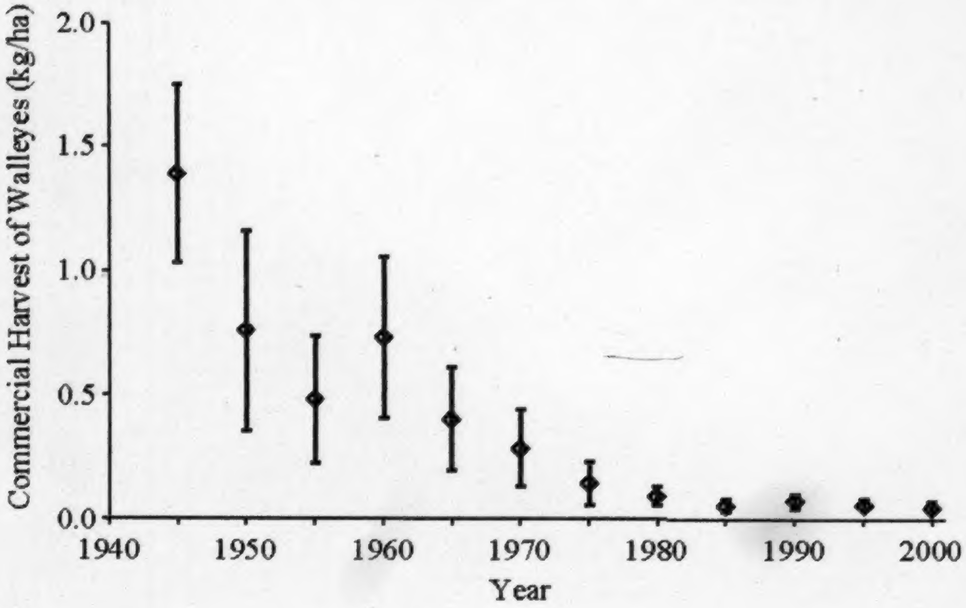

Figure 4. Commercial harvest (kg/ha) of walleye from six lakes (La Biche, Calling, Touchwood, Wolf, Beaver, and Moose lakes) in Alberta during 1940–2000. Diamonds depict five-year averages and whiskers depict 95% confidence intervals.

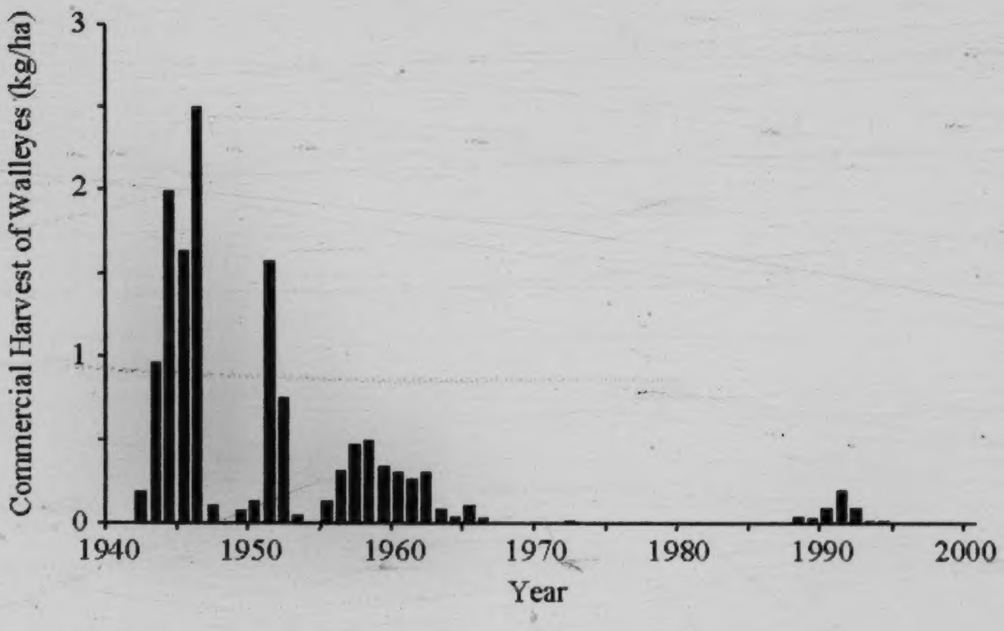

Figure 5. Commercial harvest of walleye from Lac La Biche, Alberta, during 1942–2000.

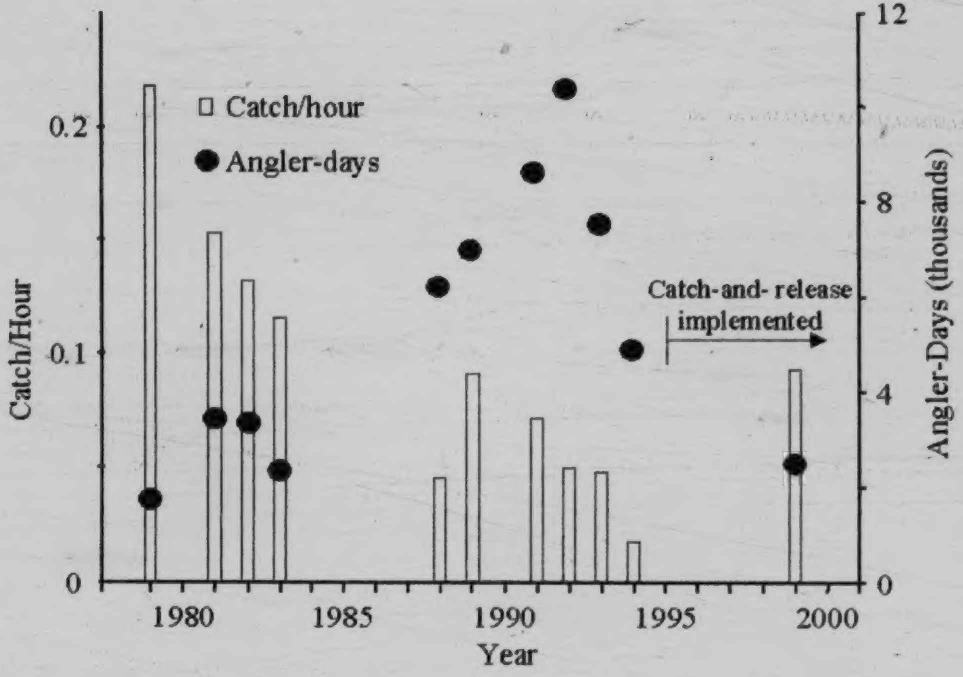

Figure 6. Angling catch rate (catch/hour) of walleye and angling effort (angler days) during the summer recreational fishery at Wolf Lake, Alberta during 1979–1999.

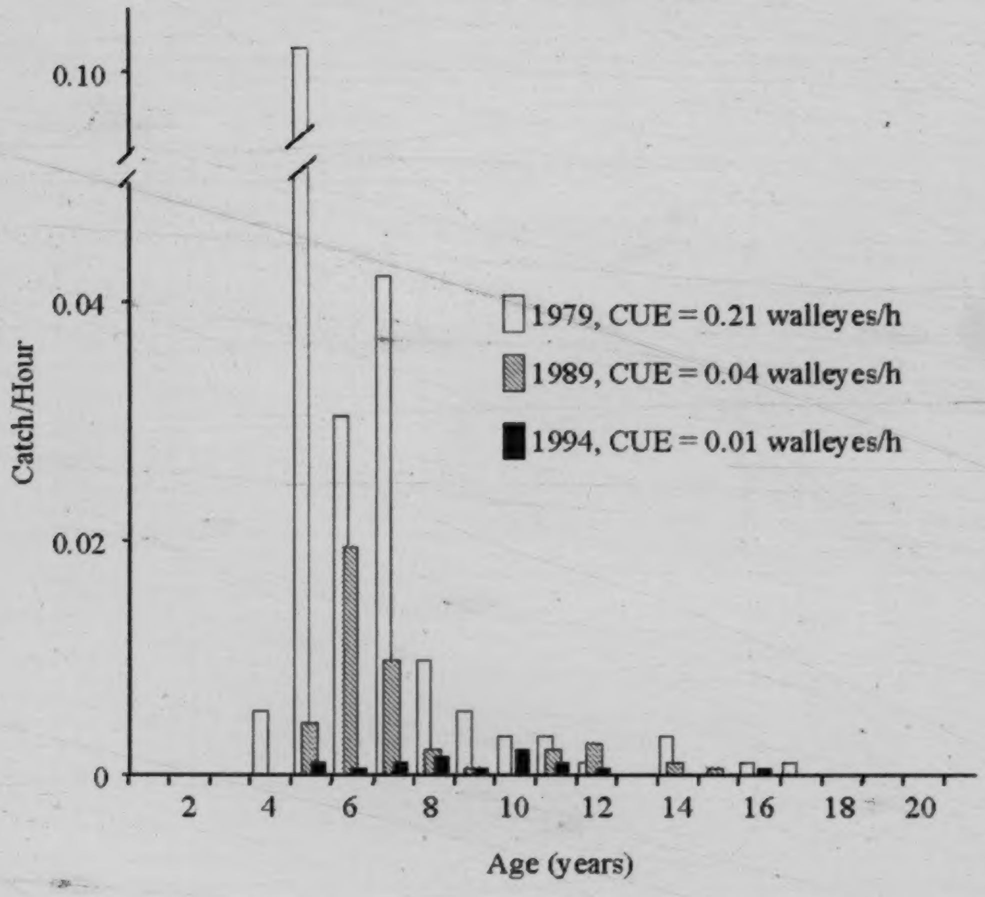

Figure 7. Age distribution, derived from annuli on sectioned fin spines and rays, and angling catch rate of walleye at Wolf Lake, Alberta, in 1979 (angling), 1989 (test angling), and 1994 (test angling).

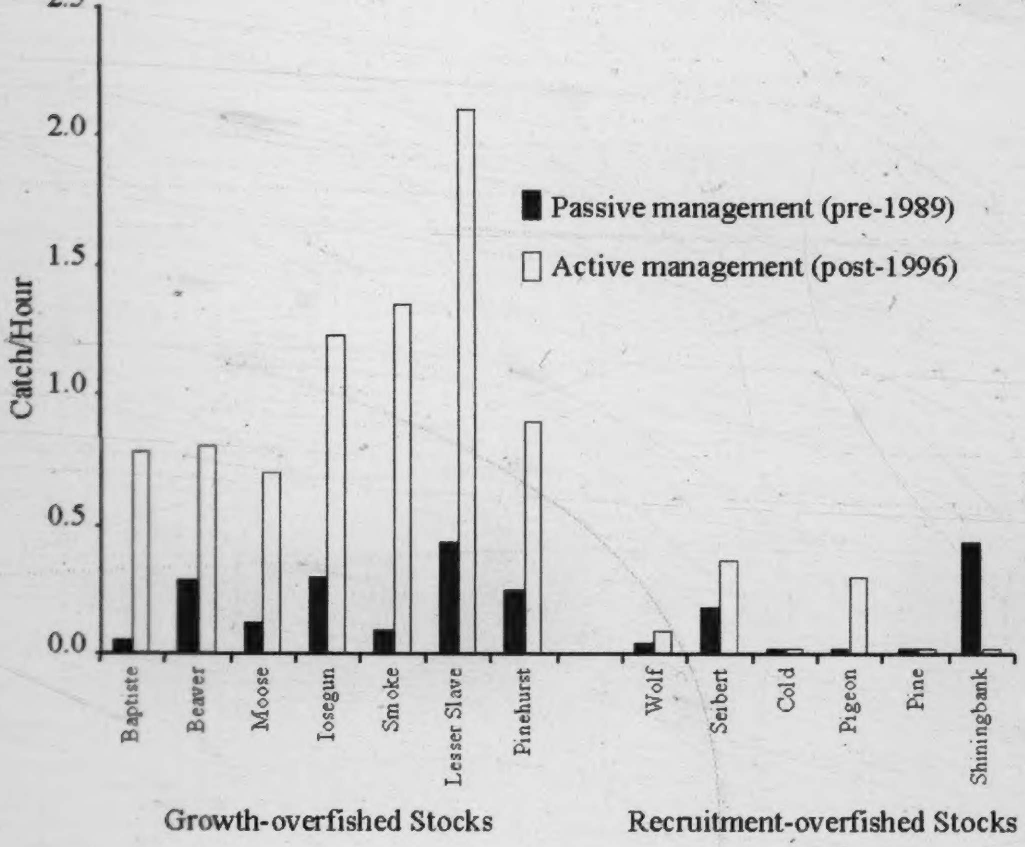

Figure 8. Angling catch rate of walleye from the period (pre-1989) of passive management (primarily creel limits), when stocks were growth-overfished, and from the period (post-1996) of active management (primarily highly restrictive length limits), when stocks were recruitment-overfished, in Alberta.

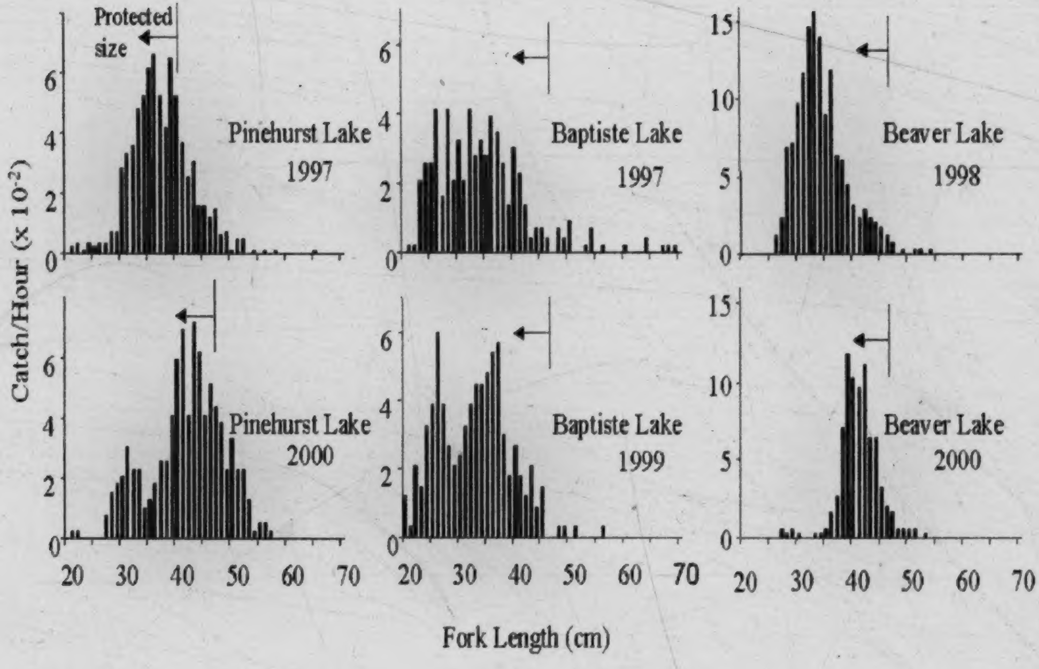

Figure 9. Length frequency distribution of walleye caught by test angling (angling with no length-limit restrictions) at three Alberta lakes with recovering walleye stocks. The minimum length limit in the angling fishery at each lake is depicted by the vertical line and arrow (the length limit was increased at Pinehurst Lake in 1998).

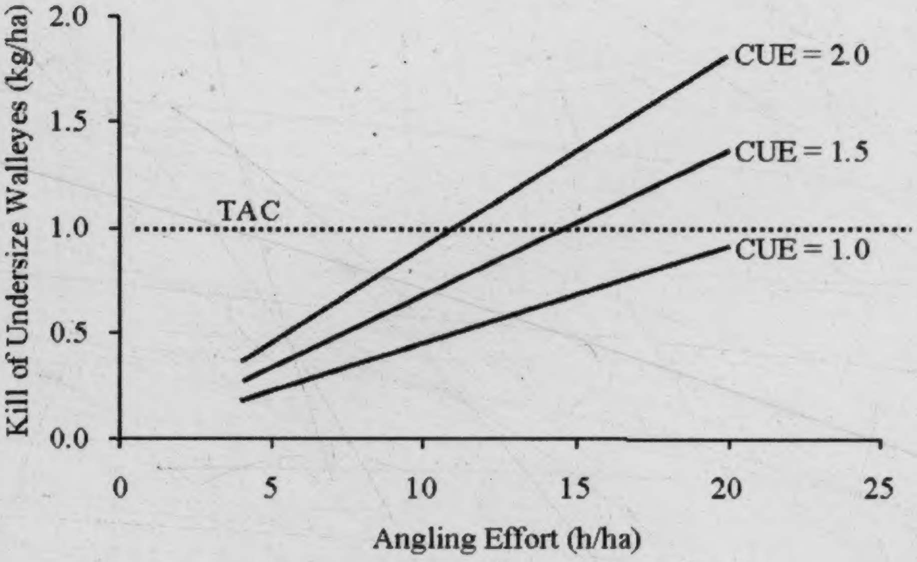

Figure 10. Theoretical relationship between angling effort (h/ha) and kill of undersize walleye (kg/ha) in an angling fishery with three different catch rates (fish/h), 5% hooking mortality, and 5% illegal harvest on undersize fish (with a mean weight of 453 g). The TAC (total allowable catch; 1 kg/ha) is estimated for stable Alberta walleye fisheries.

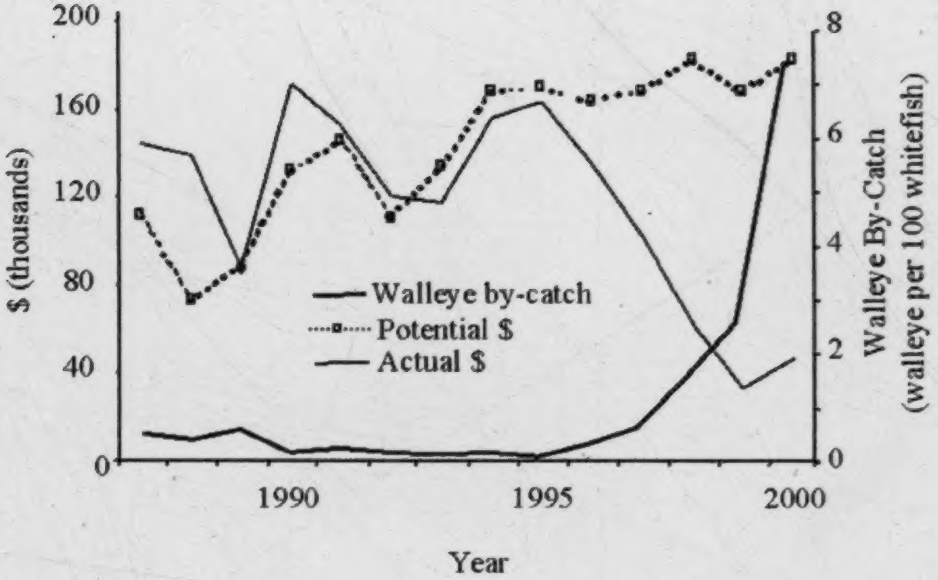

Figure 11. By-catch of walleye and potential and actual values of the commercial fishery for lake whitefish at Pigeon Lake, Alberta, during 1987–2000.

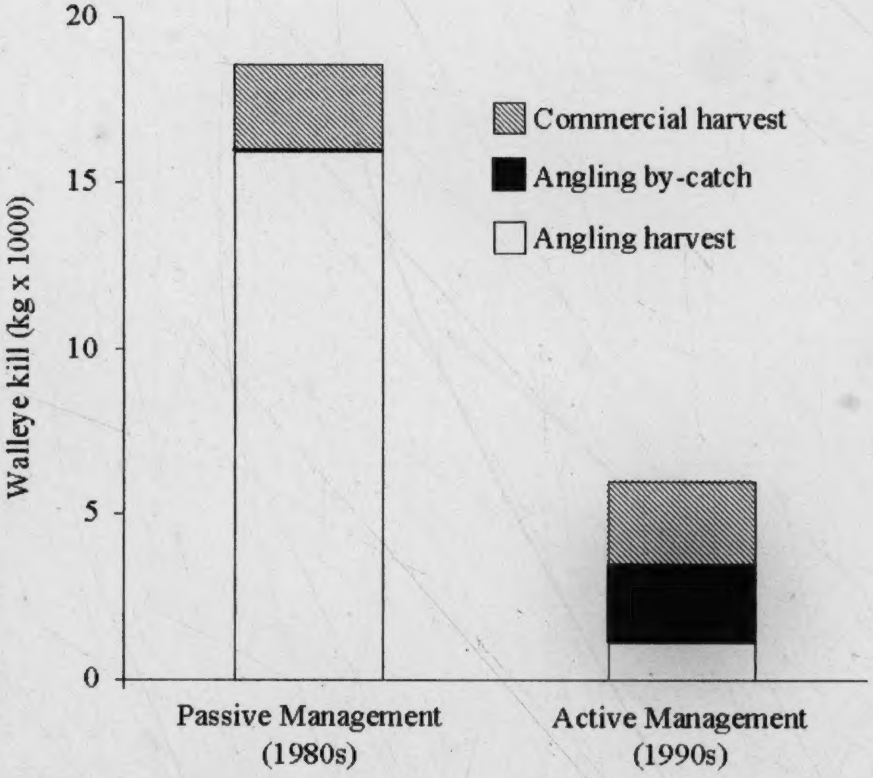

Figure 12. Walleye harvested by recreational and commercial fisheries from Touchwood, Ste. Anne, Cold, Beaver, Moose, Kehiwin, and Ironwood lakes in Alberta during periods of passive (1982–1986) and active (1994–1999) management of angling fisheries. Angling harvest includes legally harvested walleye and angling by-catch includes the kill caused by 5% hooking mortality and 5% illegal harvest of undersize fish.

Appendix 1. Biophysical data for study lakes.

Table A.1. Geographical, limnological, and fisheries data for Alberta study lakes. Data from Mitchell and Prepas (1990), unless otherwise indicated.

Lake	Latitude	Longitude	Area (ha)	Mean depth (meters)	TDS (mg/l)	Conductivity (ms/cm)	Trophic status[b]	History of commercial fisheries[c]	Public access[d]	Walleye stock status[e]
Amisk	54^0 35'	112^0 37'	530	15.5	221	299	Eutrophic	Extensive	Good	Collapsed
Athabasca	59^0 05'	110^0 00'	77,7000	20	47	87	Oligotrophic	Extensive	Poor	Stable
Baptiste	54^0 45'	113^0 33'	980	8.6	188	331	Hyper-eutrophic	Low	Good	Vulnerable
Beaver	54^0 43'	111^0 50'	3,310	7.1	227	409	Mesotrophic	Extensive	Good	Vulnerable
Bistcho[a]	59^0 45'	118^0 50'	39,900	3.7	n/a	n/a	n/a	Extensive	Poor	Stable
Calling	55^0 15'	113^0 19'	13,800	n/a	94	168	Eutrophic	Extensive	Good	Unclassified
Cold	54^0 33'	110^0 05'	37,300	49.9	133	249	Oligo-mesotrophic	Extensive	Good	Vulnerable
Ethel	54^0 32'	110^0 21'	490	6.6	163	300	Mesotrophic	Extensive	Good	Collapsed
Floatingstone	54^0 13'	111^0 38'	590	n/a	250	438	Eutrophic	Low	Good	Collapsed
Frenchman[a]	54^0 35'	111^0 48'	990	n/a	179	330	n/a	Extensive	Good	Collapsed
Gardiner[a]	57^0 25'	112^0 50'	1,910	n/a	n/a	n/a	n/a	None	Poor	Vulnerable

Garner	54° 12'	111° 14'	620	8.1	545	867	Mesotrophic	Low	Good	Collapsed
Gregoire	56° 27'	111° 08'	2,580	3.9	60	117	Eutrophic	Low	Good	Collapsed
Hilda[a]	54° 31'	110° 26'	330	5.3	368	690	Mesotrophic	Moderate	Moderate	Vulnerable
Iosegun	54° 28'	116° 50'	1,340	4.1	79	139	Eutrophic	Extensive	Moderate	Vulnerable
Ironwood[a]	54° 36'	111° 31'	980	8.5	184	230	n/a	Extensive	Moderate	Collapsed
Kehiwin[a]	54° 04'	110° 54'	620	6.7	275	405	n/a	Extensive	Good	Collapsed
La Biche	54° 50'	112° 03'	23,400	8.4	154	288	Eutrophic	Extensive	Good	Collapsed
Lesser Slave	55° 25'	115° 25'	116,000	11.4	103	201	Eutrophic	Extensive	Good	Vulnerable
Moore	54° 13'	110° 31'	930	8.3	400	717	Mesotrophic	Low	Good	Collapsed
Moose	54° 15'	110° 55'	4,080	5.6	389	657	Eutrophic	Extensive	Good	Vulnerable
Muriel	54° 09'	110° 40'	6,320	6.6	714	1143	Mesotrophic	Extensive	Good	Collapsed
Net[a]	58° 10'	110° 50'	260	2.7	n/a	n/a	n/a	None	Poor	Vulnerable
North Buck	54° 41'	112° 32'	1,900	2.5	172	326	Eutrophic	Extensive	Good	Collapsed
North Leland[a]	59° 52'	111° 00'	1,520	n/a	n/a	n/a	n/a	None	Poor	Stable
North Wabasca[a]	56° 00'	113° 50'	9,940	5.8	n/a	n/a	n/a	Extensive	Moderate	Stable
Pigeon	53° 01'	114° 02'	10,360	6.2	155	283	Eutrophic	Extensive	Good	Collapsed
Pinehurst	54° 39'	111° 25'	4,070	12.2	152	280	Eutrophic	Moderate	Good	Vulnerable
Primrose[a]	54° 48'	110° 00'	43,630	3.0	146	n/a	n/a	Extensive	Restricted	Stable

Shiningbank[a]	53^0 52'	116^{0}01'	470	3.3	209	349	n/a	Moderate	Moderate	Collapsed
Seibert	54^0 43'	111^{0}19'	3,790	6.9	301	547	Mesotrophic	Low	Moderate	Vulnerable
Skeleton	54^0 37'	112^{0}43'	790	6.5	181	333	Eutrophic	Extensive	Good	Collapsed
Smoke	54^0 22'	116^{0}56'	1,000	5.1	91	179	Eutrophic	Extensive	Moderate	Vulnerable
Spencer[a]	54^0 48'	111^{0}15'	1,710	4.1	172	311	n/a	Extensive	Restricted	Stable
Ste. Anne	53^0 42'	114^{0}25'	4,980	4.8	165	305	Eutrophic	Extensive	Good	Collapsed
Touchwood	54^0 49'	111^{0}23'	2,900	14.8	146	268	Mesotrophic	Extensive	Good	Collapsed
Wabamun	53^0 32'	114^{0}35'	7,800	6.3	235	417	Eutrophic	Extensive	Good	Collapsed
Wolf	54^0 42'	110^0 57'	3,150	9.2	156	300	Mesotrophic	Extensive	Moderate	Collapsed
Release[a]	58^0 10'	110^{0}50'	230	5.4	n/a	n/a	n/a	None	Poor	Vulnerable

[a] Alberta Fish and Wildlife Division file data

[b] based on chlorophyll *a* (Mitchell and Prepas 1990)

[c] none = no commercial fisheries for walleyes in past 60 years; low = <10 commercial fisheries in past 60 years; moderate = 10–30 commercial fisheries in past 60 years; extensive = annual commercial fisheries for more than 60 years.

[d] poor = fly-in or winter road; moderate = gravel road or 4x4 access; good = paved road; restricted = military base (public access restricted)

[e] based on 2002 Alberta Guide to Sport Fishing Regulations

n/a = data not available

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Chapter 2. Illegal Angling Harvest of Walleye Protected by Length Limits in Alberta

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Abstract.—The sport fishery for walleye (*Sander vitreus*) in Alberta, Canada, has declined severely as a result of high angling pressure relative to the low productivity of northern fisheries. Following extensive public consultation, highly restrictive length and bag limits were implemented on all walleye fisheries, clearly increasing the opportunities and temptations for anglers to illegally harvest fish. An estimate of illegal harvest was derived from data gathered at 20 sport fisheries in Alberta from 1991 to 1998. The technique involved counting protected-length fish in anglers' creels and comparing these numbers to the numbers of protected-length fish released. I avoided anglers' exaggeration of released walleye numbers by comparing the ratios of lengths of fish caught by test angling to those of fish retained and reported by anglers, as recorded by creel clerks. The average illegal harvest level was high (18.4% of protected-length walleye caught were kept, range = 0.2% - 68.8%). Illegal harvest was lowest at fisheries with catch-and-release regulations and highest at fisheries managed with slot-length limits. Of particular importance to fisheries managers, illegal harvest was inversely related to catch rate, thereby creating a strong depensatory response to a fishery decline. Other indices of compliance (creel clerks' reports of illegal harvest, the percentage of protected-length fish in anglers' creels, and angler infraction rates) were less useful indicators of illegal harvest. To counteract the negative effects of illegal harvest, managers should (1) avoid using length limits at lakes expected to have high illegal harvest levels, (2) use slot-length limits only at lakes where catch rates are expected to be high, and (3) not rely on low infraction rates or low percentages of protected-length fish in creels to imply high levels of compliance.

Introduction

Hilborn and Walters (1992) and Ludwig et al. (1993) argue that human motivation and responses are among the most critical aspects of resource management. One of these responses, noncompliance with restrictive harvest regulations, is often assumed to be a significant factor in the success or failure of fisheries and wildlife management strategies (Brousseau and Armstrong 1987; Barnhart 1989; Smith et al. 1989). Gigliotti and Taylor (1990) used a simulation model to demonstrate that modest levels of noncompliance could negate any benefits gained from implementing minimum-length limits or catch-and-release fisheries. In field studies, however, illegal harvest probably can never be measured with complete accuracy (Cowles et al. 1979; Schill and Kline 1995). Anglers with protected-length fish may avoid check stations or hide fish, or they may exaggerate their catches of released fish. Both activities (underreporting of protected-length fish and overreporting of released fish) will result in an underestimate of the true level of illegal harvest. Because of these problems, researchers are estimating relative indices of illegal harvest using a variety of methods, such as random response questionnaires (Schill and Kline 1995), reports of simulated violations (Boxall and Smith 1987), tallies by creel clerks (Paragamian 1984; Martin 1995), and recovery of tags from protected-length fish (Pierce and Tomcko 1998).

The negative effects of illegal harvest are most severe when angling pressure is high relative to biological production, or in cases where a management strategy requires the release of a large proportion of the catch. Both of these conditions face biologists managing walleye sport fisheries in Alberta. Located near the northern edge of the range of walleye (Scott and Crossman 1973), Alberta has relatively few lakes (approximately 200) with suitable walleye habitat (Mitchell and Prepas 1990; Berry 1995). Growth rates are slow and maturity is late (ages 8 - 20 for female walleye), so fisheries are unproductive. In conjunction with these limited fisheries, Alberta has a large and burgeoning human population, of which more than 300,000 are anglers. Walleye are the most popular sport fish in the province. Most lakes have easy road access, and angling pressure is heavy relative to fish production. This combination of factors has resulted in many poor and declining fisheries, with more than 90% of anglers being unsuccessful in harvesting a walleye during a fishing trip. To restore these fisheries, the angling public was heavily involved in developing regulations that would be effective and socially acceptable. Based on their input, very restrictive length limits that required anglers to release more than 85% of their walleye catch were implemented in 1996. The opportunity and temptation for noncompliance with these regulations is high and should be considered in the management strategy.

To quantify the illegal harvest of protected-length walleye in Alberta, I compared creel clerk tallies of illegally retained fish in anglers' creels to estimates of numbers of released, protected-length walleye (derived from test-angling data). Using this technique, I estimated the illegal harvest at 20 fisheries from 1991 to 1998. I also monitored the illegal harvest at an additional nine fisheries with catch-and-release regulations by using anglers' reports of released fish and creel clerk tallies of harvested fish. I compared my measure of illegal harvest to other commonly used indices of compliance, such as creel clerks' reports of illegal harvest, the percentage of protected-length fish in anglers' creels, and angler infraction rates.

Study Area

Study lakes were located in northern Alberta and had public access via paved or all-weather roads. The sizes of the lakes ranged from 301 ha to 23,400 ha. Walleye, northern pike (*Esox lucius*), and yellow perch (*Perca flavescens*) were the only sport species caught by anglers, with walleye being the most desirable fish. Sport fishing regulations for walleye included catch-and-release, protected slot-length limits, and minimum-length limits of 38, 43, and 50 cm total length (TL). Because of the wide variation in catch rates and quality of fisheries between years, each year of study at each lake is referred to as a separate fishery or study. Descriptions of the fishes and aquatic habitats of Alberta are found in Nelson and Paetz (1992) and Mitchell and Prepas (1990).

Methods

Creel survey.—Data were collected from single-site, completed-trip creel surveys of the sport fishery during the summer angling season. At the lakes surveyed, virtually all anglers fished from boats. Creel clerks interviewed all anglers returning to the boat launch on each survey day (including the few anglers fishing at night). Survey days included 50% of the weekends and holidays and 25% of the weekdays. Creel clerks collected angler-use data and information from the anglers' catch. Biological samples were taken from a random subset of harvested fish. The numbers of protected-length and legal-length walleye harvested by anglers were determined from direct tallies of the harvested fish (i.e. fish in the anglers' creels, as counted by creel clerks). Catch rate (CUE) is the catch divided by the reported angler effort. The catch refers to both harvested and released walleye, unless otherwise noted.

I designed field procedures that would prevent anglers from altering their normal (and possibly illegal) behavior. Anglers who violated the length-limit regulations were not charged with an offence or reprimanded by the creel clerks. Creel clerks were not in uniform, had no enforcement authority, and in most cases, were not members of the governmental Fish and Wildlife Division, but rather employees of a nonprofit conservation organization. Local field enforcement officers were never notified that a compliance study was in progress, and consequently, their enforcement efforts were routine.

Illegal harvest.—To quantify illegal harvest, only two values are needed: the number of protected-length walleye kept and the number of protected-length walleye released. The creel clerk tally of protected-length walleye in the anglers' harvest was a direct count and was used as the first parameter. The second parameter could be anglers' reports of released protected-length walleye; however, anglers may exaggerate the numbers of fish they have released (Essig and Holliday 1991; Pollock et al. 1994), which reduces the estimate of illegal harvest. To avoid this exaggeration and more accurately estimate the numbers of released fish, test angling was used to determine the ratio of protected-length to legal-length walleye in an angling fishery. This ratio was then extrapolated to the sport fishery, using the creel clerks' tallies of legal-length walleye. This single extrapolation provided the required estimate of the number of released, protected-length walleye, and thereby allowed illegal harvest to be quantified.

Fisheries staff and volunteers (including anglers recruited at the lakes by the creel clerks) test angled at the study lakes during creel surveys. Test fisheries were conducted weekly throughout the season to avoid seasonal size selectivity of walleye. Test anglers were directed simply to catch walleye using whatever lures or techniques they would normally use when angling at these lakes. All test-angled walleye were measured, a pelvic fin section was removed for marking and estimating age, and the fish were released.

To extrapolate the length ratio of walleye from the test fisheries to the sport fisheries, and thereby estimate the number of protected-length walleye caught by anglers, I used Bailey's modification of the Petersen index (Ricker 1958). This technique is analogous to a population estimate using mark-recapture data, where the ratio of a smaller number of animals (captured animals : recaptured tagged animals) is extrapolated to estimate the ratio of a larger number of animals (total population : total tagged animals). Consequently, the following terms may be employed:

N = estimate of total catch of all lengths of walleye in the sport fishery,

M = number of legal-length walleye observed in the sport fishery,

c = number of walleye in the test fishery,

r = number of legal-length walleye in the test fishery, and

$N = M\,(c + 1) / (r + 1)$

The estimate of the number of protected-length walleye caught in the sport fishery is simply $N - M$. Illegal harvest was calculated as the number of protected-length walleye counted in anglers' creels / $(N - M)$. I assumed that anglers released 10% of legal-length walleye. Confidence limits for the estimate of N were obtained using the exact method for binomial proportions (Zar 1999). Confidence limits for illegal harvest were calculated as the number of protected-length walleye counted in anglers' creels / each confidence limit of N – M. Where the number of protected-length walleye counted was larger than the confidence limit of N – M, the illegal harvest confidence limit would, therefore, exceed 100%. The estimated values of N – M were also used in the calculation of catch rate.

Illegal harvest was observed and, therefore, not estimated at one fishery (the North Saskatchewan River). River anglers were entirely shore-based at the creel sites, and the creel clerks saw and measured all walleye that were kept or released. The illegal harvest at this fishery was calculated simply as the number of protected-length walleye harvested / the number of protected-length walleye caught.

Results

Illegal Harvest

Data were collected at 20 walleye fisheries, and 43,488 anglers were interviewed (Table 1). Of the 9,305 walleye tallied from the sport harvest, 7,794 were legal-length and 1,511 were protected-length. A total of 52,949 protected-length walleye were reported to have been released by anglers. In the test fisheries, 3,802 walleye were sampled.

Estimates of illegal harvest varied widely among fisheries, ranging from 0.2% to 68.8%, with an average estimate of 18.4% (Table 1, Figure 1). The two lakes with slot-length limits had much higher illegal harvest rates (mean of 29.2%, n = 7 fisheries) than did the fisheries managed with minimum-length limits (mean of 12.6%, n = 13 fisheries).

Illegal harvest was strongly related to the catch rate of protected-length walleye and increased exponentially with decreasing catch rate ($r^2 = 0.66$, df = 19, $P < 0.01$; Figure 2). Only 2 of the 12 fisheries with catch rates lower than 0.2 walleye / h had illegal harvest rates of less than 10%.

At fisheries with low illegal harvest levels (less than 10%), lengths of most of the illegally harvested walleye were within 2 cm of the length limit (Figure 3). At fisheries with higher levels of illegal harvest, the lengths of illegally harvested walleye were spread over a much larger range (Figure 4). At fisheries with protected slot-length limits, anglers illegally kept protected-length walleye near both length-limit boundaries (Figure 5).

Indices of Compliance

Creel clerk tally of illegal harvest.—Illegal harvest, as calculated using creel clerks' tallies of protected-length walleye in anglers' creels, was strongly correlated to anglers' reported numbers of released walleye. The average creel clerks' tally of illegal harvest was 7.4% (range = 0.4% - 30.8%; Table 2) and was strongly correlated to the estimated illegal harvest ($r^2 = 0.79$, df = 19, $P < 0.01$; Figure 6a), but was nearly three times lower than that estimated using test fishery data.

Ratio of protected-length fish in creel.—A high percentage of the walleye from anglers' creels were protected-length fish (mean = 35.7%, range = 1.7% - 85.7%; Table 2). The percentage of protected-length walleye from the anglers' harvest was significantly related to the estimated illegal harvest ($r^2 = 0.44$, df = 19, $P < 0.01$; Figure 6b).

Angler infraction rate.—At lakes with high illegal harvest levels, catch rates were low. Clerks would, therefore, encounter few anglers with walleye, and even fewer anglers with illegally harvested walleye. The proportion of anglers with protected-length walleye in their possession, the angler infraction rate, was 3.1% (range = 0.3% - 12.8%; Table 2). The infraction rate was not significantly related to the estimated illegal harvest ($r^2 = 0.07$, df = 19, $P = 0.27$; Figure 6c), and infraction rates could be orders of magnitude lower than illegal harvest rates.

Illegal Harvest at Fisheries with Catch-and-Release Regulations

At nine of the fisheries studied, angling regulations required that all walleye caught by anglers be released (Table 3). Because most anglers only reported (not showed) any part of their catch of walleye to the creel clerks, the test fisheries could not be used to quantify the ratio of lengths of walleye, and thereby avoid exaggeration. Illegal harvest using test-fishery data could not, therefore, be estimated at these fisheries. Only one harvested walleye was counted by creel clerks at one of the nine fisheries. The overall rate of reported illegal harvest was 0.4% (1 walleye illegally kept out of 253 reported to have been released).

Discussion

Assumptions of Estimating Illegal Harvest

These estimates of illegal harvest should be considered minimum values because several factors contribute to biases that would cause illegal harvest to be underestimated. I based my calculations on the numbers of protected-length fish that anglers voluntarily showed to creel clerks. If anglers concealed protected-length fish (as seems probable), the actual illegal harvest level would be higher than estimated. For example, if anglers concealed 25% of fish taken illegally, the estimate of illegal harvest would rise by 25% (i.e. an illegal harvest of 10% would become 12.5%). The unexpectedly low rate of reported illegal harvest at lakes with catch-and-release regulations could, therefore, partially be a result of anglers hiding walleye. The creel clerks were generally of the opinion that anglers felt it was a minor offense to keep protected-length walleye, but that it was more serious to keep fish from a strictly catch-and-release lake. This relative weighting of offenses may contribute to anglers concealing protected-length walleye.

At all study lakes, following government policy, a creel survey was advertised to be in progress, with signs at the lakes and articles in local newspapers. This knowledge may contribute to a decrease in illegal activity, which would result in an underestimation of the illegal harvest rates that may have occurred in the absence of a study (Pierce and Tomcko 1998).

A major assumption of my technique for estimating illegal harvest is that the length distribution of walleye caught by test anglers is the same as the length distribution of walleye caught by sport anglers. Using my analogy to a mark-recapture population estimate, this encompasses a host of specific assumptions (e.g. mixing of marked fish, immigration, mortality, and tag loss), which all address the single general assumption that the ratios of marked to unmarked fish are equal in the sample and in the population. For example, a bias would exist if test anglers were more skilled and could catch larger walleye than could sport anglers. This bias would, again, tend to cause the illegal harvest to be underestimated. Although test fisheries were designed to simulate the sport fishery (using skilled and unskilled anglers, recruited locally, fishing on a range of dates, and using a variety of gear), the assumption of equal ratios should be tested at fisheries without length limits, where anglers may keep all walleye caught. No lakes in my jurisdiction meet this criterion, and I was unable to test this assumption. Catch rates for the two different types of fisheries do not need to be comparable as they are not used in this analysis.

Confidence limits around the index of illegal harvest were large, primarily as a result of the small sample sizes of legal-length walleye from the test fisheries. In two cases, these confidence limits exceeded the logical limit of 100%, a result of the tallied number of illegally harvested fish exceeding the lower confidence limit of the estimated number of fish caught. In Alberta, studies using test angling to correct for anglers' exaggeration now focus on the number of legal-length fish caught in the test fishery to optimize the effort required in test-angling fisheries and to minimize the confidence limits.

In my calculations, I assumed that anglers released 10% of legal-length walleye, although the average reported release rate was 23%. If this value was exaggerated to the same degree as was the reported catch of protected-length walleye, my assumption of a 10% release rate would be reasonable. Altering this parameter has relatively little effect on the illegal harvest level. For example, if anglers released 20% of legal-length walleye and not 10%, my estimate of illegal harvest would increase by 10% (i.e. a 10% estimate would become 11%). Conversely, if anglers released no legal-length walleye, my estimate of illegal harvest would decrease by 10% (i.e. a 10% estimate would become 9%). Because of generous bag limits (3 walleye / day), low catch rates (average = 0.034 legal-length walleye / h, range = 0.005 – 0.127), and the high desirability of large walleye, the release rate for legal-length walleye was probably not more than 10%.

Creel clerks did not enforce the length-limit regulations in any official manner. At most, offending anglers were casually informed that their fish were not in the legal length range. This nonintervention was necessary to collect accurate data, but also created some controversy among enforcement staff. Observing violations and not responding to them may be a contravention of the policies of certain resource management agencies. Prior to conducting similar studies, other researchers should clarify these legal issues with the appropriate enforcement authorities.

Comparisons of Indices of Compliance

My index of illegal harvest was used to estimate the number of protected-length fish harvested compared to the number that were caught. This is the definition of illegal harvest that Gigliotti and Taylor (1990) used in their simulations of noncompliance with regulations. Because of the difficulty in estimating this parameter, other researchers have used more readily available indicators of compliance. The infraction rate, defined as the proportion of anglers encountered with protected-length fish, has been used by Paragamian (1984) and Pierce and Tomcko (1998) as a measure of noncompliance. Schill and Kline (1995) also used infraction rate, with data derived from random response tests. At fisheries where most anglers do not catch any fish, such as many present-day Alberta walleye fisheries, the proportion of anglers who harvest protected-length fish is necessarily small and does not reflect compliance with length limits. In my study, there was no correlation between estimated illegal harvest and infraction rate.

Glass and Maughan (1984) and Pierce and Tomcko (1998) also used the proportion of protected- versus legal-length fish sampled during creel surveys as measures of compliance. This measure would be a function of the population structure as well as the illegal harvest level. In my study, the percentage of protected-length walleye in the anglers' creels was only moderately predictive of illegal harvest. A high proportion of illegal fish in the creel did not necessarily imply that illegal harvest was also high.

Paragamian (1984) defined noncompliance as the number of anglers harvesting protected-length smallmouth bass (*Micropterus dolomieui*) compared to the total number of successful anglers. I was unable to calculate this measure of noncompliance because I could not accurately determine the number of successful anglers, if success is defined as catching, but not necessarily retaining a fish. This is a very difficult parameter to quantify because anglers may lie as to whether they have or have not caught (and released) a fish. In this study, most anglers reported catching only one fish. I suspect, therefore, that most of the exaggeration in the creel data was from anglers who caught nothing, but reported that they caught one fish. Paragamian (1984) described the smallmouth bass length limit as being successful because only 4% of the protected-length smallmouth bass caught were also kept. This definition of illegal harvest is similar to my use of the term "illegal harvest," but Paragamian used anglers' verbal reports of the numbers of protected-length fish that were released and, therefore, he could neither check nor correct for exaggeration errors. Gabelhouse (1984) also used anglers' reports of illegal harvest to determine compliance with slot-length limits for largemouth bass (*Micropterus salmoides*) and found that no more than 14% of protected-length fish that were caught were harvested. In my study, although anglers' reports of illegal harvest were strongly correlated to the estimated illegal harvest, the average reported value (7.4%) was only 40% of the estimated value (18.4%). This difference is solely the result of anglers exaggerating the numbers of protected-length walleye that they released.

Management Implications

Fisheries management.—Illegal harvest of walleye increased sharply at low catch rates, creating a strong depensatory response to declining fish stocks. This has very serious implications for fisheries managers attempting to protect declining fish populations. Under these circumstances, when managers require that a protective length limit be most effective (high fishing pressure combined with low catch rates), the response of many anglers will be to ignore the length limit. Compliance with the regulation would likely be higher at fisheries with high catch rates, where protective regulations are unnecessary or of lesser importance. In Alberta, this depensatory effect was probably strong enough to negate management efforts related to walleye population recovery. Of the five fisheries in this study with illegal harvest rates greater than 15%, four have recently been reclassified as collapsed and have been closed to the sport harvest of walleye.

The negative effects of high illegal harvest levels are ameliorated somewhat by a reduction in angler effort at fisheries with very low catch rates. When walleye fisheries in Alberta collapse, a time lag of several years occurs before anglers abandon the fishery. Once collapsed, the illegal harvest level may be high, but few anglers are involved, and fewer actually catch any walleye, so the absolute volume of illegal harvest is small. Illegal harvest would be most severe during a declining fishery, when catch rates are low, but anglers have not yet responded to the decline by abandoning the fishery. These conditions (high angler effort, low catch rate, and high illegal harvest levels) would cause the fishery to decline at a much faster rate. In Alberta, each local fisheries biologist must manage dozens to hundreds of separate lakes and rivers. Assessing the status of a fishery and responding effectively to a decline requires more time than is available for all fisheries. Inadequate management is exacerbated when the rate of decline increases because of illegal harvest.

In this study, catch-and-release regulations appeared to elicit much higher levels of compliance than did length limits, which may be because anglers at catch-and-release fisheries are expecting to harvest no fish and are, therefore, less tempted to cheat when the opportunity arises. Anglers at fisheries managed with length limits would have some expectation of harvesting fish, and may, therefore, be tempted to illegally satisfy this expectation, especially when fishing is poor. Slot-length limits resulted in twice the level of illegal harvest as minimum length limits, with the length distribution of fish suggesting that anglers were tempted to cheat at both margins of the slot. Slot-length limits may elicit higher compliance when catch rates are so high that anglers are not forced to decide whether to cheat or go home fishless.

To counteract the negative effects of the illegal harvest of walleye in Alberta, fisheries managers may modify the sport fishing regulations at those lakes expected to have high illegal harvest levels (i.e. those fisheries with low catch rates) by imposing a bag limit of zero (mandatory catch-and-release). Large minimum-length limits (43 or 50 cm) are used at fisheries with moderate catch rates. Slot-length limits are not presently used in Alberta to recover overfished populations.

Enforcement.—Preventing high illegal harvest levels by increasing enforcement may be impractical. Because the highest illegal harvest occurs at lakes with the lowest catch rates, enforcement officers will encounter few anglers with any fish, and even fewer with protected-length fish. Apprehension of violators will, therefore, be a rare event, and this factor is not directly related to illegal harvest. In this study, at fisheries with illegal harvest rates greater than 20%, the average infraction rate observed by creel clerks was only 4%. The value of the infraction rate as an index of illegal harvest is further reduced as a result of enforcement officers interviewing anglers during incomplete angling trips. Enforcement officers conducting on-the-water checks will be interviewing anglers who are, on average, halfway through their fishing trip. The infraction rate calculated using this incomplete trip data will, therefore, be only 50% of that calculated using completed trip data. At study lakes with high levels of illegal harvest (>20%), the infraction rate measured in this way would have been 2% (i.e. 98% of anglers encountered on the lake would have had no protected-length walleye in their creel). The infraction rate was not related to the estimate of illegal harvest using the test-angling data. The fishery with the highest infraction rate (13%) had a relatively low illegal harvest level (6%). This lack of relationship between illegal harvest and encounters with violators has also been shown in other studies. Pierce and Tomcko (1998) reported high levels of tag returns (19%) from protected-length northern pike from seven Minnesota lakes, yet officers saw only two violations after coming in contact with 165 angling parties. Gabelhouse (1984) reported that in five years of studies at slot-limit lakes in Kansas, no tickets were written for length-limit violations. Paragamian (1984) found that 7% of anglers encountered by conservation officers were in violation of the length limit for smallmouth bass from Iowa streams, in spite of good levels of compliance.

At my study lakes, enforcement officers typically patrolled once every 10 days. Officers would interview from 5 to 30 anglers per visit. Most patrols, therefore, did not result in any encounters with violators. Even doubling or tripling the patrol frequency would not result in the apprehension of a significant proportion of the total number of violators and would be well beyond the budget limitations of our enforcement branch. Although the potential for apprehension may be a primary aspect of compliance, increasing enforcement to levels at which violators were commonly apprehended would be impractical.

Another aspect of the difficulty of changing enforcement efficiency is the desire of officers to patrol lakes at which catch rates are highest and to ignore fisheries with low catch rates. Officers would describe "wasting their time checking people without fish" and, rather, would want to patrol at lakes with high catch rates, where they believed that they would have a greater chance of catching people with protected-length fish. Based on the results of this study, this behavior would actually decrease the probability of encountering violators.

Education.—The length distributions of illegally harvested walleye indicate that anglers were generally aware of the length-limit regulations, but chose to ignore them at lakes with low catch rates. At lakes with higher catch rates, most of the protected-length walleye sampled were within 2 cm of the length limit. Paragamian (1982) found that a large proportion of the protected-length largemouth bass kept were within 1.3 cm of the length limit at an Iowa reservoir. At Alberta lakes with low catch rates, the protected-length walleye taken were not near the length limit. Glass and Maughan (1984) reported that the large illegal harvest of largemouth bass at an Oklahoma reservoir was composed of fish obviously smaller than the length limit. The high illegal harvest of northern pike reported by Pierce and Tomcko (1998) was also associated with a large proportion of fish well beyond the slot-length limit boundaries.

Increased education about regulations would probably have little effect in reducing illegal harvest. Most anglers with protected-length fish appeared to know about the regulations. When the creel clerks were measuring anglers' fish, those with protected-length fish would usually pay close attention. Comments such as "Am I close?", "How did I do?", or "I think it's a little short." were very common and indicated that these anglers knew of the length limit. Other typical reasons given by anglers for keeping protected-length walleye were that the fish was badly injured or that it was the only fish caught that day. Rarely would an angler claim ignorance of the length limit. Biologists in Alberta are currently attempting to quantify anglers' knowledge of lake-specific regulations.

During the years of this study, length limits were strongly emphasized in the regulation booklet available to all licensed anglers. Most lakes had signs at the access points describing the specific length limit for that lake. Extensive media coverage describing the regulations was provided, and the importance of compliance was emphasized. At the study lakes, the length limit was often specifically explained to anglers, and some anglers were given measuring tapes marked with the limits. In spite of this intensive, personal education, there were several instances of these same anglers returning to the creel clerks with protected-length fish.

The contention of Hilborn and Walters (1992) and Ludwig et al. (1993) that human motivation and responses are among the most critical aspects of resource management is supported by this study. When sport fisheries in Alberta declined to seriously low levels, a series of human responses were initiated that counteracted effective management (i.e. despite education, low catch rates resulted in illegal harvest, creating conditions for inefficient enforcement). Precautionary management (Mangel et al. 1996; Richards and Maguire 1998) implies that fisheries managers must be aware of these reactions and subsequently plan strategies to avoid the conditions that cause them.

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Table 1. Summary of lake area, walleye length limit, and parameters used to estimate illegal harvest at 20 Alberta walleye sport fisheries. Prot. = numbers of protected-length walleyes. Legal = numbers of legal-length walleyes. Illegal harvest = protected kept / protected caught. Both estimates are shown with upper and lower 95% confidence limits.

			Creel survey (tallies from interviews)				Test angling		Estimates	
Lake and year of study	Area (ha)	Length limit TL (cm)	No. of Anglers	No. of Hours	Prot. kept	Legal kept	Prot.	Legal	Prot. caught[b]	Illegal harvest (%)
Seibert '92	3,790	42-53 slot	2,104	6,955.0	245	41	79	9	356 (198 - 898)	69 (27 - 124)
Seibert '93	3,790	42-53 slot	2,030	6,366.0	145	32	136	6	684 (357 - 2207)	21 (7 - 41)
Seibert '94	3,790	42-53 slot	1,036	3,310.5	38	27	104	15	193 (119 - 381)	20 (10 - 32)
Touchwood '91	2,900	42-53 slot	2,512	6,640.0	17	95	59	50	121 (83 - 183)	14 (9 - 20)
Touchwood '92	2,900	42-53 slot	3,785	10,348.0	72	85	91	45	185 (131 - 277)	39 (26 - 55)
Touchwood '94	2,900	42-53 slot	3,477	9,547.0	105	147	92	40	363 (254 - 553)	29 (19 - 41)
Touchwood '97	2,900	42-53 slot	2,947	8,444.5	117	313	109	41	894 (634 - 1,345)	13 (9 - 18)
Baptiste '97	981	50 min.	825	2,888.5	11	78	255	17	1,216 (788 - 2,246)	1 (0 - 1)
Elinor '96	933	50 min.	938	2,665.0	12	17	133	6	355 (185 - 1,150)	3 (1 - 6)

Hilda '97	337	50 min.	290	717.0	6	11	54	3	163 (71 - 1,088)	4 (1 - 8)
May '96	301	50 min.	72	253.0	4	2	92	31	6 (4 - 10)	63 (39 - 93)
Rock Is. '96	2,078	50 min.	501	1,619.5	20	61	24	14	107 (57 - 241)	19 (8 - 35)
N. Sask. R. '97	n/a	50 min.	451	1,132.5	10	15	n/a	n/a	115 (n/a)	9 (n/a)
Beaver '98	3,310	50 min.	2,037	6,427.0	16	74	522	4	8,498 (4,114 - 38,681)	0 (0 - 0)
Smoke '98[a]	959	43 min.	958	2,844.0	47	124	202	8	3,061 (1,714 - 8,080)	2 (1 - 3)
Iosegun '98[a]	1,340	43 min.	907	2,815.5	191	271	395	33	3,463 (2,498 - 5,253)	6 (4 - 8)
Shiningbank '98	463	43 min.	1,178	2,538.0	5	13	5	6	10 (3 - 47)	49 (11 - 174)
Pinehurst '97	4,070	43 min.	3,414	12,217.5	189	1,039	595	118	5,715 (4,721 - 7,085)	3 (3 - 4)
Pinehurst '93	4,070	38 min.	8,845	28,541.0	225	3,229	49	34	4,973 (3,238 - 8,178)	5 (3 - 7)
Pinehurst '94	4,070	38 min.	5,181	16,756.5	36	2,120	191	135	3,275 (2,633 - 4,144)	1 (1 - 1)
Totals (or means)	1,789		43,488	133,026.0	1,511	7,794	3,187	615	33,754	18.4

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[a] prot. kept derived by extrapolation of the ratios of protected-length : legal-length fish in the biological samples to the tallies of harvested fish

[b] rounded to whole number in table

Table 2. Illegal harvest compared to other indices of compliance at 20 Alberta walleye sport fisheriesfrom 1991 to 1998.

			Indices of compliance		
Lake and year of study	Length limit TL (cm)	Illegal harvest [a]	Creel clerks' tallies of illegal harvest[b]	Protected-length walleyes in creel[c]	Angler infraction rate[d]
Seibert '92	42-53 slot	69% (245 / 356)	19% (245 / 1,272)	86% (245 / 286)	11% (223 / 2,104)
Seibert '93	42-53 slot	21% (145 / 684)	9% (145 / 1,544)	82% (145 / 177)	7% (134 / 2,030)
Seibert '94	42-53 slot	20% (38 / 193)	7% (38 / 515)	59% (38 / 65)	3% (35 / 1,036)
Touchwood '91	42-53 slot	14% (17 / 121)	6% (17 / 286)	15% (17 / 112)	1% (14 / 2,512)
Touchwood '92	42-53 slot	39% (72 / 185)	18% (72 / 399)	46% (72 / 157)	2% (60 / 3,785)
Touchwood '94	42-53 slot	29% (105 / 363)	12% (105 / 841)	42% (105 / 252)	3% (90 / 3,477)
Touchwood '97	42-53 slot	13% (117 / 894)	5% (117 / 2,128)	27% (117 / 430)	3% (102 / 2,947)
Baptiste '97	50 min.	1% (11 / 1,216)	1% (11 / 1,690)	12% (11 / 89)	1% (8 / 825)
Elinor '96	50 min.	3% (12 / 355)	2% (12 / 566)	41% (12 / 29)	1% (10 / 938)
Hilda '97	50 min.	4% (6 / 163)	3% (6 / 231)	35% (6 / 17)	1% (4 / 290)
May '96	50 min.	63% (4 / 6)	31% (4 / 13)	67% (4 / 6)	3% (2 / 72)
Rock Is. '96	50 min.	19% (20 / 107)	6% (20 / 341)	25% (20 / 81)	3% (16 / 501)

N. Sask. R. '97	50 min.	9% (10 / 115)	9% (10 / 115)	40% (10 / 25)	2% (7 / 451)
Beaver '98	50 min.	0% (16 / 8,498)	0% (16 / 4,526)	18% (16 / 90)	1% (13 / 2,037)
Smoke '98	43 min.	2% (47 / 3,061)	1% (47 / 3,704)	28% (47 / 171)	4% (34 / 958)
Iosegun '98	43 min.	6% (191 / 3,463)	6% (191 / 3,172)	41% (191 / 462)	13% (116 / 907)
Shiningbank '98	43 min.	49% (5 / 10)	8% (5 / 60)	28% (5 / 18)	0% (3 / 1,178)
Pinehurst '97	43 min.	3% (189 / 5,715)	2% (189 / 7,881)	15% (189 / 1,228)	4% (120 / 3,414)
Pinehurst '93	38 min.	5% (225 / 4,973)	1% (225 / 16,946)	7% (225 / 3,454)	2% (135 / 8,845)
Pinehurst '94	38 min.	1% (36 / 3,275)	0% (36 / 8,230)	2% (36 / 2,156)	0% (21 / 5,181)

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[a] number of protected-length walleyes kept / estimated number of protected-length walleyes caught (rounded to whole numbers)

[b] number of protected-length walleyes kept / reported number of protected-length walleyes caught

[c] number of protected-length walleyes kept / total number of walleyes kept

[d] number of anglers keeping protected-length walleyes / total number of anglers

Table 3. Summary of lake area and illegal harvest parameters at nine Alberta fisheries with catch-and-release regulations in effect.

Lake and year of study	Area (ha)	Number of anglers interviewed	Reported number of angler-hours	Reported catch of walleyes	Tallied illegal harvest of walleyes
Amisk '96	515	292	611.5	2	0
Ethel '97	490	439	1,098.0	76	0
Fickle '98	456	525	1,115.0	25	0
Floatingstone '97	588	254	505.0	5	0
Garner '98	619	1,295	2,685.5	12	0
Lac La Biche '98	23,400	972	4,228.5	12	1
North Buck '98	1,900	1,367	3,239.0	1	0
Skeleton '97	789	75	145.0	0	0
Vincent '97	728	352	664.5	120	0
Totals		5,571	14,292.0	253	1

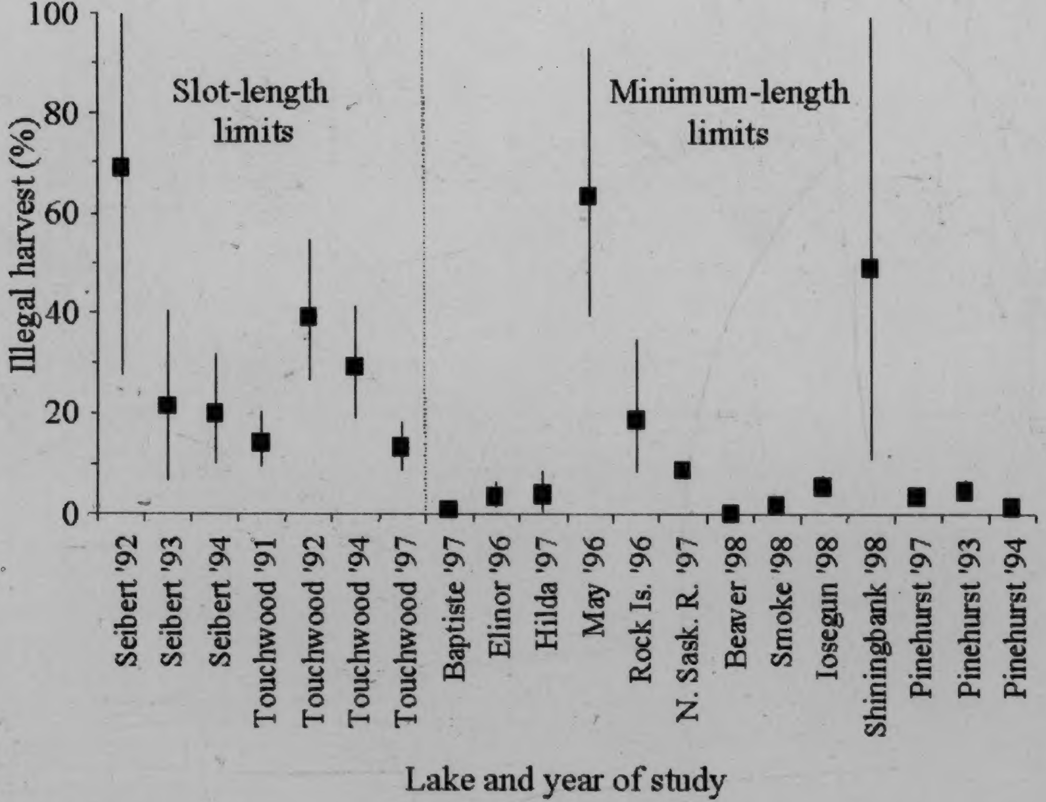

Figure 1. Estimates of illegal harvest of walleye by anglers violating length-limit regulations at 20 Alberta fisheries, 1991 - 1998. Illegal harvest is defined as the number of protected-length walleye that were kept compared to the number of protected-length walleye that were caught. Whiskers are 95% confidence intervals (truncated, in two cases, at 100%).

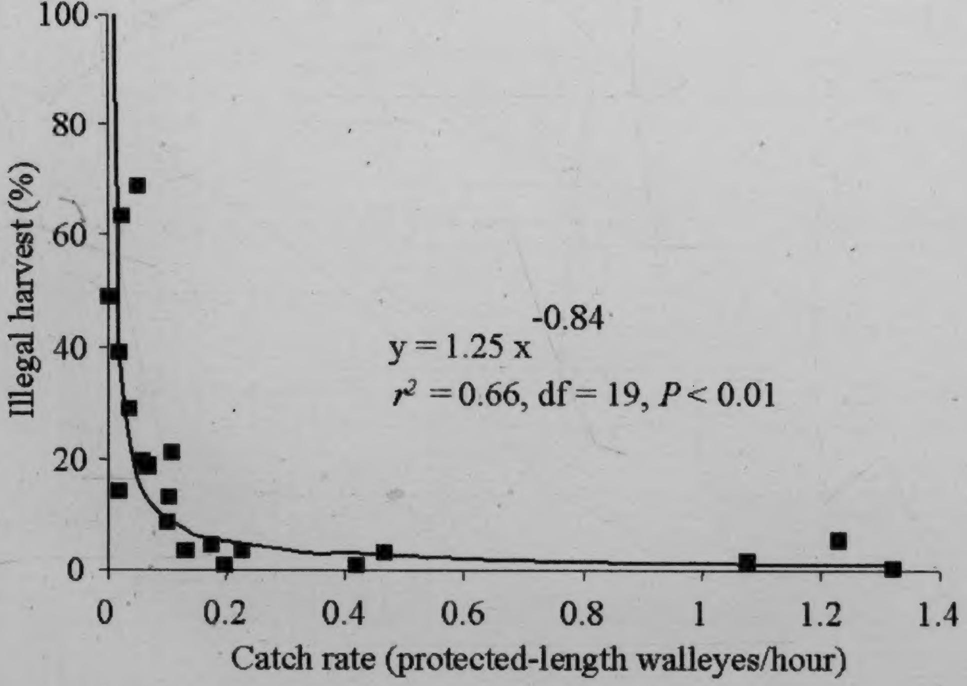

Figure 2. Relationship between illegal harvest and catch rate of protected-length walleye at 20 Alberta fisheries, 1991-1998. Variance of residuals is constant (score test for nonconstant variance, $P = 0.19$; Weisberg 1985).

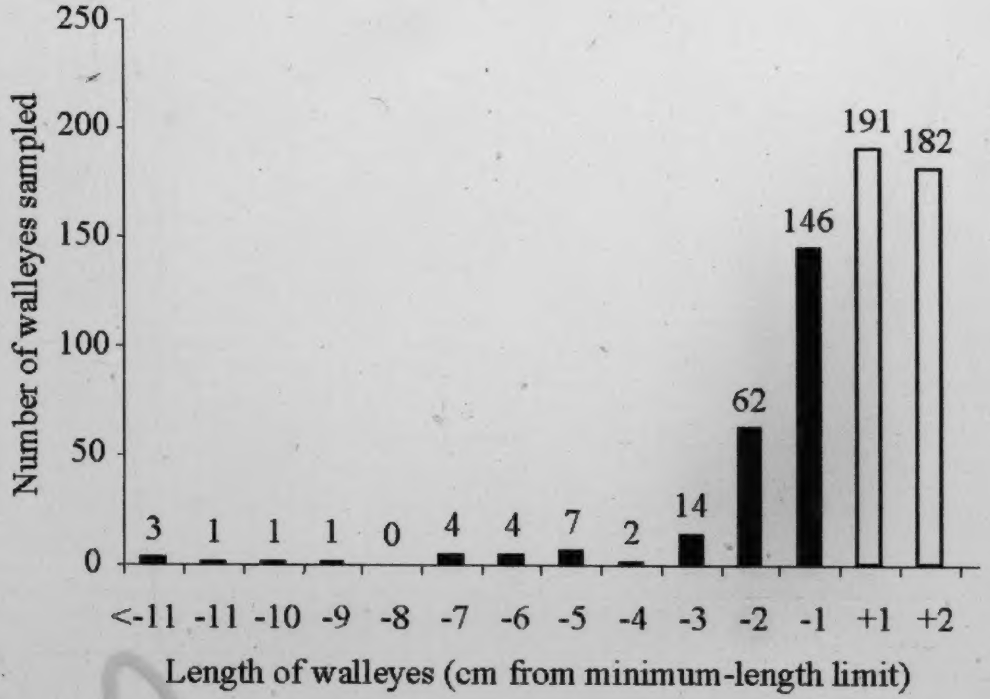

Figure 3. Lengths of harvested walleye at fisheries with low rates of illegal harvest (less than 10%) and with minimum-length limit regulations in effect. Lengths are in relation to the minimum-length limit in each fishery (black bars represent illegally harvested walleye, clear bars represent legally harvested walleye). Data are from nine fisheries in Alberta: 245 protected-length walleye were sampled, and 23,395 anglers were interviewed.

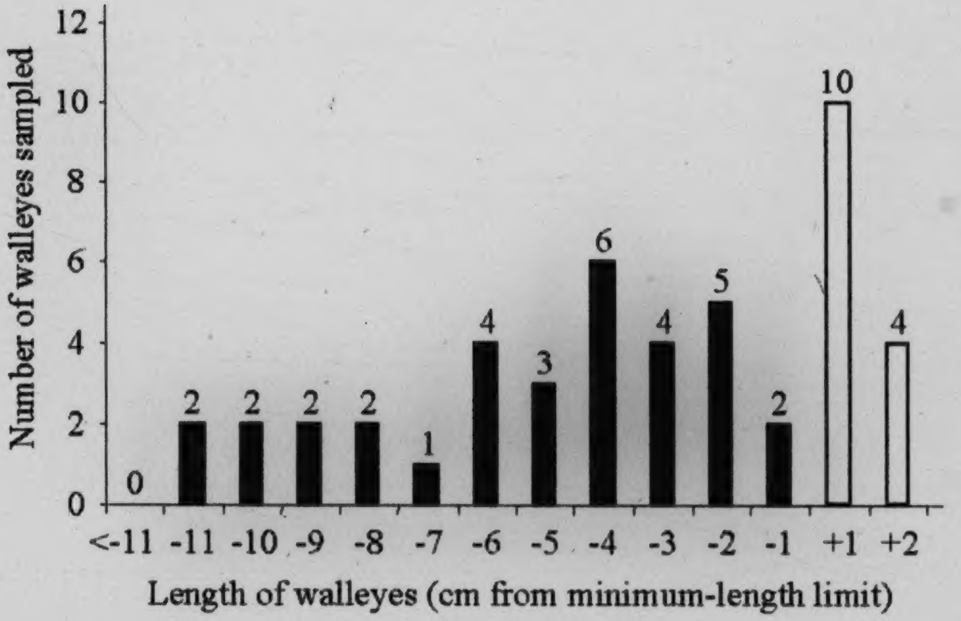

Figure 4. Lengths of harvested walleye at fisheries with high rates of illegal harvest (greater than 10%) and with minimum-length limit regulations in effect. Lengths are in relation to the minimum-length limit in each fishery (black bars represent illegally harvested walleye, clear bars represent legally harvested walleye). Data are from four fisheries in Alberta: 33 protected-length walleye were sampled, and 2,202 anglers were interviewed.

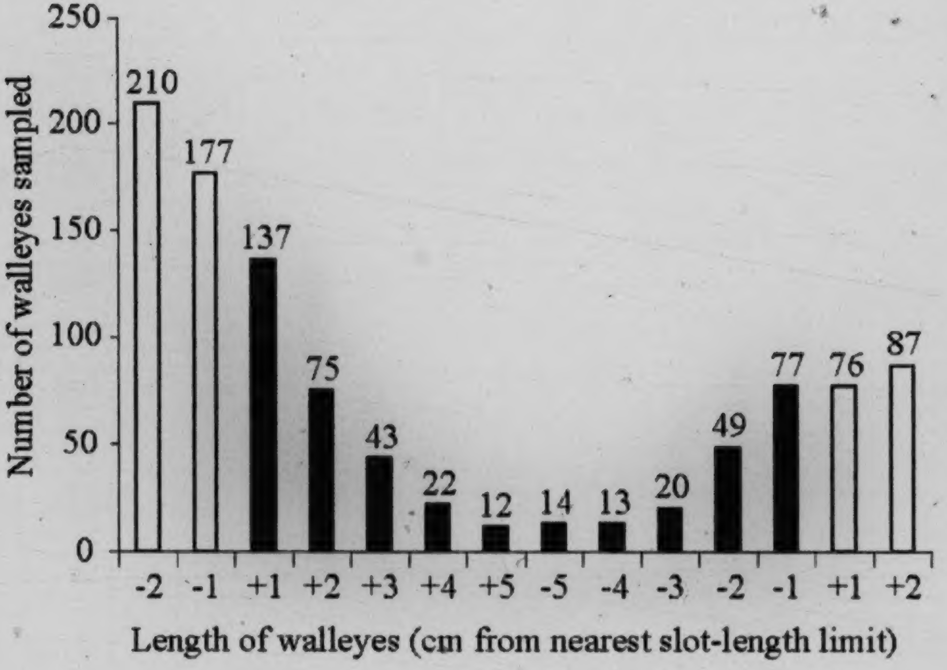

Figure 5. Lengths of harvested walleye at fisheries with protected-length slot limits in effect. Lengths are in relation to the slot-length limit in each fishery (black bars represent illegally harvested walleye, clear bars represent legally harvested walleye). Data are from seven fisheries in Alberta: 462 protected-length walleye were sampled, and 17,891 anglers were interviewed.

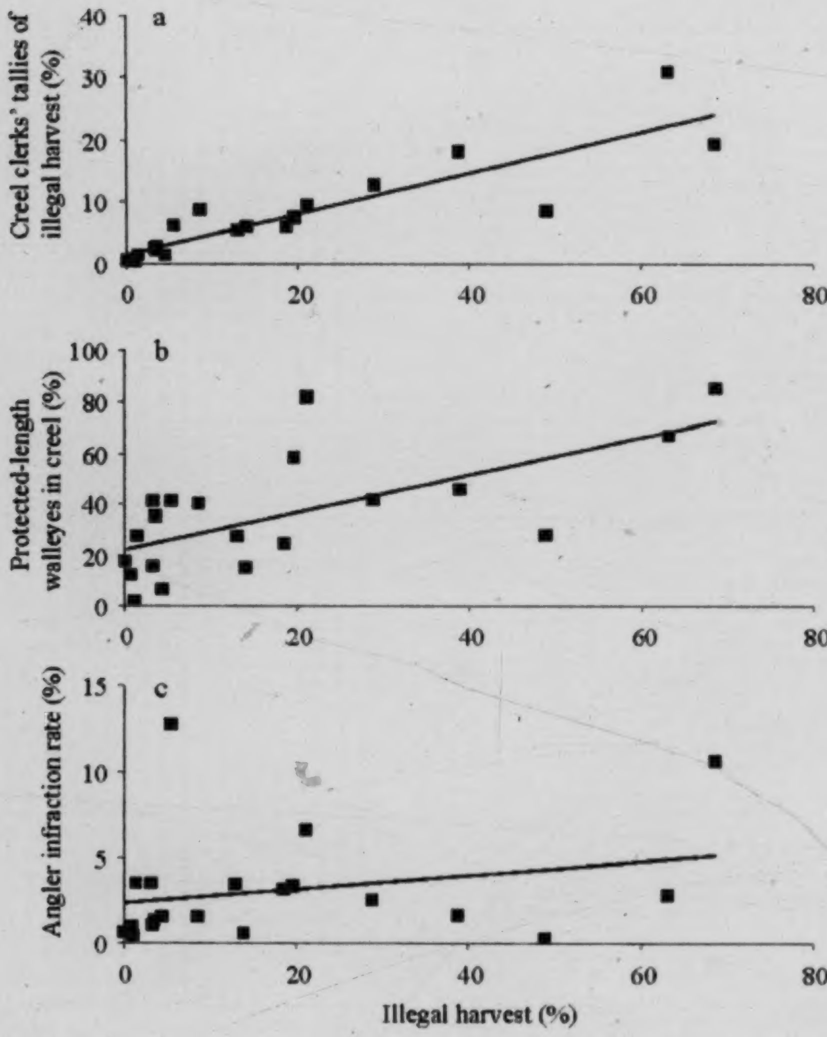

Figure 6. Relationships between estimates of illegal harvest and a) creel clerks' tallies of the percentage of protected-length walleye that were caught and illegally harvested ($r^2 = 0.79$, df = 19, $P < 0.01$), b) the percentage of protected-length walleye in anglers' creels ($r^2 = 0.44$, df = 19, $P < 0.01$), and c) angler infraction rate ($r^2 = 0.07$, df = 19, $P = 0.29$). Data are from 20 Alberta fisheries, 1991-1998.

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Chapter 3. Exaggeration of Walleye Catches by Alberta Anglers

Sullivan, M. G. 2003. Exaggeration of walleye catches by Alberta anglers. North American Journal of Fisheries Management 23:641–648.

Abstract.— I studied anglers' exaggeration of catches of walleye *Sander vitreus* at Alberta sport fisheries to determine whether trends in reported catches were indicative of actual trends. To quantify anglers' exaggeration, I compared the ratios of protected-length to legal-length walleye as reported by anglers to similar ratios confirmed from test angling at 22 walleye sport fisheries from 1991 to 2000. Overall, anglers reported catching 2.2 times more protected-length walleye per legal-length walleye than were caught in the test-angling fisheries. Exaggeration in catches was not constant, but increased exponentially with decreasing catch rate. On-site exaggeration, in combination with further exaggeration in mail surveys results in the reported catch rate declining at a lower rate than the actual catch rate, thereby causing a perception of hyperstability in the fishery. Hyperstability has profound implications for biologists who manage fisheries based on reported data, because reported catch rates may provide little warning of a fisheries collapse.

Introduction

Many sport fisheries are managed using catch-and-release or length-limit regulations, so fisheries managers must increasingly rely on anglers' reports of fish catches as a monitoring tool, rather than observation and counting of the harvest. Managers must also depend on reported catches whenever catches are not directly observed, such as through mail and telephone surveys. Errors in reporting the actual catch using off-site techniques have both been assumed (Essig and Holliday 1991; Pollock et al. 1994) and demonstrated (Claytor and O'Neil 1991; Roach et al. 1999). Generally, off-site survey techniques should not be used for estimating catch (Jacobson et al. 1983). The low cost of these techniques, however, provides a strong motivation for using indirect methods as fisheries monitoring tools (Smith 1983; Weithman and Haverland 1991).

On-site creel surveys are generally preferred to off-site techniques and are assumed to yield accurate harvest data because creel clerks can directly observe and tally anglers' catch (Newman et al. 1997). Huntsman et al. (1978), however, noted that on-site surveys do not allow for calculation of the true numbers of released fish because anglers may exaggerate their catches when reporting to creel clerks.

Fisheries managers often assume that exaggeration by anglers is constant and trends in reported catches are indicative of stock status (MacDonald and Dillman 1968; Huntsman et al. 1978; Jacobson et al. 1983). By accepting this assumption, managers can use the reported catch as an index of harvest or abundance and supposedly illustrate trends in the actual catch or catch rate. In contrast (and prior) to these authors, Jenson (1964) described how fisheries managers in California stopped using mail surveys as indices for salmon and steelhead fisheries because known harvest trends were not shown.

In Alberta, anglers' catch reports have become increasingly important as a monitoring tool. The sport fishery for walleye in Alberta exerts heavy fishing pressure on boreal systems with low productivity. Walleye harvest rates at accessible fisheries were typically below 0.1 fish per angler-hour, and more than 90% of anglers were unsuccessful in harvesting a walleye during a fishing trip (Berry 1995). In 1996, restrictive angling regulations were imposed on all walleye fisheries in Alberta. Many fisheries became catch-and-release only, with most of the remainder being managed using large (43 or 50 cm total length, TL) minimum length limits. Anglers must now typically release more than 85% of their walleye catch.

The main technique for monitoring walleye sport fisheries in Alberta involves access-point creel surveys at individual lakes. Creel surveys are necessary to determine angler effort, as well as harvests of walleye and other fish species (mainly northern pike *Esox lucius* and yellow perch *Perca flavescens*). Assessment of the status of walleye fisheries depends on biological data collected from anglers' harvests and on catch data derived from interviews with anglers. With the increase in catch-and-release regulations, monitoring became more dependent on reported trends.

My objectives were to test the assumption that anglers exaggerate their catch, and, if true, to determine whether exaggeration is constant with respect to the actual catch. To meet these objectives, I developed a technique for comparing the length ratios of walleye caught in test-angling fisheries to the length ratios reported and observed in the creel surveys. I used this technique in studies from 1991 to 2000 at 22 walleye sport fisheries in Alberta. I also analyzed data from the published literature to quantify the additional exaggeration that occurs between the time of on-site creel surveys and mail surveys.

Methods

I conducted my research in northern Alberta (north of 54^0 latitude), at a series of easily accessible and popular sport fishing lakes (Table 1), and have treated each year of study at each lake as a separate fishery. Most anglers fished exclusively for walleye, although some also reported catching northern pike and yellow perch. Much of this work was part of a study of angler compliance, and the study sites, methods, and a discussion of the assumptions are described in greater detail in Sullivan (2002).

In brief, anglers reported catching and releasing a number of protected-length walleye, but I doubted the accuracy of their reports. To estimate the actual number of protected-length walleye that were caught, I used the following method. Creel clerks tallied anglers' catch of legal-length walleye and anglers' reported catch of protected-length walleye. Test angling was used to estimate the ratio of protected-length walleye to legal-length walleye caught in the sport fishery. I then extrapolated this test-fishery ratio to the sport fishery using anglers' catch of legal-length walleye as the denominator. The resulting numerator is my estimate of the number of protected-length walleye caught in the sport fishery. Bailey's modification of a Lincoln-Petersen index (Ricker 1958) was used in this extrapolation. Confidence intervals for the estimate of numbers of protected-length walleye caught in the sport fishery were calculated using the exact method for binomial proportions (Zar 1999). Exaggeration was calculated as the number of protected-length walleye that anglers reported catching compared to the estimated number of protected-length walleye that were caught.

I also analyzed data from Roach et al. (1999) to quantify anglers' exaggeration in mail surveys (using their Tables 2 and 3, catch per day, to derive exaggeration) and could thereby combine the two levels of angler exaggeration.

Angler catch and harvest data were collected from access-point, completed-trip creel surveys of sport fisheries during the summer angling season. Creel clerks interviewed all anglers returning to the survey access-point during each survey day. Surveys involved two levels of sampling intensity: anglers were interviewed on either 70% or 35% of all days from mid-May to mid-August. At the study lakes, virtually all anglers fished from boats and were interviewed upon returning to shore from their fishing trips. Creel clerks asked anglers the number of hours that they had spent fishing and the number of protected-length walleye that they had released. All harvested walleye were tallied and a random subset was sampled for biological information.

Creel clerks were not in uniform, had no enforcement authority, and were instructed to be as casual and nonofficial as possible.

To derive the ratio of protected-length to legal-length walleye caught in the sport fishery, fisheries staff and local volunteers test angled for walleye at the study lakes. To avoid possible seasonal size selectivity, a variety of dates were chosen for fishing throughout the angling season (mean = 15.6 different test-fishing dates at each lake, range = 5-32, Table 1). On each test-fishery day, at least 2 anglers, and as many as 60, would participate. Test anglers were instructed to catch walleye using whatever lures or techniques they would normally use when angling at these lakes. All walleye caught in test fisheries were measured to the nearest millimeter fork length (FL) and then released.

Catch rates were calculated as total ratio estimators (Malvestuto 1983). Catch refers to the number of fish caught, which includes both harvested and released fish, unless otherwise stated. Reported catch rate and on-site catch rate (used by Roach et al. 1999) are the same and are calculated from the catch and number of angler-hours reported by anglers to the creel clerks at each lake. Mail catch rate refers to the value calculated from the catch and number of angler-hours reported by anglers in mail surveys. I use angler exaggeration as a synonym for self-reporting bias (Roach et al. 1999). Angler exaggeration would encompass prestige bias and social desirability bias (MacDonald and Dillman 1968; Pollock et al. 1994). Exaggeration factor refers to the ratio of reported catch to estimated catch. Factors of 1, therefore, indicate no observed difference between reported catch and estimated catch. Exaggeration factors less than 1 mean that reporting bias is negative (i.e., anglers reported catching fewer fish than were estimated caught).

Results

From 1991 to 2000, 22 walleye fisheries were studied to estimate exaggeration factor (Table 1). The average exaggeration factor for the catch of protected-length walleye was 2.2

(Table 1). Only 2 of 22 fisheries (Iosegun 1998 and Beaver 1998) showed exaggeration factors of less than 1 (although their confidence intervals included 1), meaning that anglers may not have exaggerated at these two fisheries, but rather underestimated their catch of walleye. Both of these fisheries had high catch rates for protected-length walleye (>1.0 fish per angler-hour).

The exaggeration factor was negatively correlated with the catch rate for protected-length walleye ($r^2 = 0.69$, df = 21, $P < 0.001$, Figure 1). The reported catch rate was significantly correlated with the estimated catch rate in a log-log relationship, but declined more slowly than the estimated catch rate ($r^2 = 0.93$, df = 21, $P < 0.001$, Figure 2), showing that the bias in the reported catch rate was not constant with respect to catch rate.

This exaggeration in catch rates from on-site surveys is additive to the exaggeration from mail surveys. Roach et al. (1999) compared catch rates from a mail survey to catch rates recorded at the same lakes during on-site creel surveys. My analysis of their published data shows a good relationship ($r^2 = 0.68$, df = 17, $P < 0.001$) between exaggeration factor and on-site catch rate (Figure 3). Integration of these two levels of exaggeration (from estimated catch to on-site and from on-site to mail survey) resulted in a pattern of perceived hyperstability in catch rates, with a sudden drop in the reported catch rate at very low estimated catch rates (Figure 4).

Discussion

A major assumption of my technique for estimating anglers' exaggeration is that the length distribution of walleye caught by test anglers is the same as the length distribution of walleye caught by sport anglers. Test anglers may be more skilled, so may catch larger walleye than sport anglers, thereby creating a bias that would cause an overestimate of the exaggeration factor. To avoid this bias, test-angling techniques closely simulated those in the sport fishery (i.e., test anglers had varying skill levels, used a variety of gears, and angled throughout the fishing season). Catch rates for the two fisheries do not need to be comparable as they are not used in this analysis; only ratios of protected-length to legal-length fish were analyzed. To avoid biases caused by seasonal changes in the length frequency distribution of walleye, test fisheries were held on numerous dates throughout the summer. The length frequency distribution of walleye caught in the test fisheries, however, did not change over the angling season.

Confidence intervals around the estimates of the catch of protected-length walleye were large, primarily because of small sample sizes of legal-length walleye in the test fisheries. Although these confidence intervals often encompassed the reported catch, the best estimate of anglers' catch is the central estimate. Increasing exaggeration with declining catch rate is, therefore, the best estimate of the actual relationship. Reducing these confidence intervals was usually impractical. Many of the walleye sport fisheries were severely depressed or collapsed and had correspondingly low catch rates. It was, therefore, logistically impractical to test angle large numbers of big walleye and thereby reduce the range of the confidence intervals. When planning test-angling fisheries in Alberta, biologists now use the number of legal-length walleye to determine the sampling effort necessary to achieve the desired level of precision of catch estimate.

Because of the short time between actual catches and on-site interviews, recall bias was probably not a major factor in the exaggeration measured in my studies. Recall bias was important in the National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (Fisher et al. 1991), where reported lengths and numbers of angling trips increased with time away from the activity. Cannel et al. (1977) found that in most social surveys, as recall time increases, the reporting of an event was also likely to be distorted in a socially desirable direction. Recall bias would probably cause an increase in reported catches of fish and could be the major factor in differences between this information from on-site surveys and from mail surveys.

In this study, anglers exaggerated more as fishing success declined. People may respond to questionnaires according to their beliefs in the purpose and outcomes of testing (Page 1999).

Similarly, "role faking," in which a respondent to psychological testing answers questions in a manner that he or she perceives to be consistent with an idealized social role and not one's true identity, is believed to be a general human strategy (Kroger and Turnbull 1975). These two related psychological biases comprise prestige bias (Jacobson et al. 1983), and could be responsible for anglers exaggerating their catches of fish, especially at those lakes with very low catch rates where anglers may be embarrassed to admit that they failed to catch any fish. Prestige bias was implicated by MacDonald and Dillman (1968) in hunter surveys, where, in contrast to the male to female deer ratio brought in by hunters to check stations, deer hunters surveyed by mail reported shooting more bucks than does. Jacobson et al. (1983) provided a good review of the psychological biases associated with delayed data collection systems, as related to fisheries studies.

My data show that exaggeration occurs between the time of catching (or not catching) a fish and landing one's boat on shore. In salmonid fisheries in Maine, a similar pattern of exaggeration was shown by Roach et al. (1999), with anglers interviewed at the lake and later by mail. Further analysis of their data, as well as mine, shows that exaggeration was related to catch rate. Because exaggeration measured in mail surveys occurs after anglers have already been interviewed on shore (thereby including on-site exaggeration in their response), these two levels of exaggeration (i.e., catch exaggerated in on-site surveys and further exaggerated in mail surveys) are additive. The outcome of repeated exaggeration is probably most severe when using angler surveys, such as telephone surveys, mail surveys, internet surveys, and licence-return surveys, that are distant in time or space from the actual fishing event. The validity of using off-site surveys for monitoring fish catches should be seriously questioned where catch rates are low or declining. Acknowledging the exaggeration inherent in mail surveys, Roach et al. (1999) stated that mail survey data are better than no data at all. If the levels and trends in exaggeration seen in my study (and their study) are a general phenomenon, then such survey data would actually present a false picture by masking declines in fisheries. Unless the bias is quantified during data collection, I would refute Roach et al.'s statement and counter with the adage: "No data are better than false data." Mail surveys are useful for gathering many types of data, but catch and harvest data (and any resulting trends) should be considered suspect, especially if recall periods are long or catch rates may be declining.

In my study, which compared estimated to on-site catches, exaggeration occurred only at low catch rates. My review of published studies comparing on-site to mail surveys also showed this pattern to be common. Calhoun (1950) and Baxter and Young (1953) found no exaggeration, but used annual records involving large catches of fish (California freshwater and marine angling data). Murphy (1954) compared catch data from angler interviews and mail surveys from the Little Salmon River, Idaho, and found no consistent bias in this high catch rate fishery (>1.0 fish per angler-hour). Weithman and Haverland (1991) found that catch rates were generally underestimated in telephone surveys compared to on-site roving creel surveys at a variety of Missouri reservoirs with catch rates of >0.18 fish per angler-hour. Their harvested fish data, however, showed exaggeration at catch rates less than 0.1. Exaggeration at low catch rates was shown in the following studies: Jenson (1964) for California salmon *Oncorhynchus* spp. fisheries; Bjornn (1965) for salmon and steelhead fisheries in Idaho; MacDonald and Dillman (1968) for surveys of deer hunters; Carline (1972) for brook trout *Salvelinus fontinalis* fisheries; Claytor and O'Neil (1991) for Atlantic salmon *Salmo salar* fisheries in Nova Scotia; and Roach et al. (1999) for salmonid fisheries in Maine. Although some of this exaggeration is probably a function of nonresponse bias (Carline 1972; Connelly and Brown 1992), there also appears to be a general pattern of exaggeration at low catch rates.

Management Implications

Additive levels of exaggeration and the rate of exaggeration increasing at low catch rates (<0.1 fish per angler-hour), result in reported catch rates failing to be an index of declining catch rates. Hilborn and Walters (1992) show that hyperstability in catch rates masks the actual decline in certain fish populations. The exaggeration that I calculated from anglers' reported catches would further inflate the perception of stable fish populations. This perceived hyperstability has considerable importance to managers. As fisheries decline, anglers will increase their rates of exaggeration, and any real decline in catches is thereby masked if mail or phone survey data are used. This trend continues until actual catch rates are so low that even high levels of exaggeration result in reports of very low catch rates (i.e., at an actual catch rate of 0.005, exaggerating by a factor of 10 results in a reported catch rate of 0.05; both are still very low). In a declining fishery, initial reports result in the perception of hyperstability, followed by the perception of hyperdepletion at very low catch rates (Hilborn and Walters 1992). Fisheries managers relying on this type of data for monitoring a declining fishery may assume that the fishery is stable until confronted with a sudden and catastrophic collapse. This misperception and depensatory effect is further intensified if the actual catch rate is related to the fish population density, following a pattern of hyperstability such as that proposed by Korver et al. (1996).

The biases reported here will result in a depensatory response by anglers to declining fisheries. As fisheries decline, anglers will increase their exaggeration. Managers relying primarily on angler reports to manage a fishery will fail to detect the actual decline until the fishery collapses. Ludwig et al. (1993) stated several principles of effective resource management, of which the first two were: 1) include human motivation and responses, and 2) act before scientific consensus is achieved. The results of this study reinforce the importance of these principles.

Acknowledgments

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Management Enhancement Program and the Alberta Conservation Association. I thank Hugh Norris and Lincoln Chew for extensive assistance. John Post provided much thoughtful discussion and coined the term "perceived hyperstability." Dominic Baccante, Lee Foote, Naomi Krogman, and Heidi Zwickel provided valuable reviews and editing of this manuscript.

Table 1. Summary of lake area, walleye length limit, and parameters used to calculate exaggeration at 22 Alberta sport walleye fisheries, 1991-2000. PL = numbers of protected-length walleyes, LL = numbers of legal-length walleyes, Exag. factor = PL reported / estimated PL caught.

			Creel survey (tallies from interviews)				Test fishery			Estimates	
Lake and year	Walleye length limit[a]	Area (ha)	Anglers	Hours	PL reported	LL kept[b]	Days of test fishing[c]	PL	LL	PL caught (95% CI)	Exag. factor
Seibert '92	42-53 slot	3,790	2,104	6,955.0	1,272	41	7	79	9	356 (198-898)	3.6
Seibert '93	42-53 slot	3,790	2,030	6,366.0	1,544	32	32	136	6	684 (357-2,207)	2.3
Seibert '94	42-53 slot	3,790	1,036	3,310.5	515	27	4	104	15	193 (119-381)	2.7
Touchwood '91	42-53 slot	2,900	2,512	6,640.0	286	95	14	59	50	121 (83-183)	2.4
Touchwood '92	42-53 slot	2,900	3,785	10,348.0	399	85	18	91	45	185 (131-277)	2.2
Touchwood '94	42-53 slot	2,900	3,477	9,547.0	841	147	16	92	40	363 (254-553)	2.3
Touchwood '97	42-53 slot	2,900	2,947	8,444.5	2,128	313	19	109	41	894 (634-1,345)	2.4
Pinehurst '93	38 min.	4,070	8,845	28,541.0	16,946	3,229	7	49	34	4,973 (3,238-8,178)	3.4
Pinehurst '94	38 min.	4,070	5,181	16,756.5	8,230	2,120	13	191	135	3,275 (2,633-4,144)	2.5
Pinehurst '97	43 min.	4,070	3,414	12,217.5	7,881	1,039	9	595	118	5,715 (4,721-7,085)	1.4
Smoke '98	43 min.	959	958	2,844.0	3,704	124	6	202	8	3,061 (1,714-8,080)	1.2

Iosegun '98	43 min.	1,340	907	2,815.5	3,172	271	8	395	33	3,463 (2,498-5,253)	0.9
Shiningbank '98	43 min.	463	1,178	2,538.0	60	13	30	5	6	10 (3-47)	5.9
Baptiste '97	50 min.	981	825	2,888.5	1,690	78	16	255	17	1,216 (788-2,246)	1.4
Baptiste '99	50 min.	981	643	2,338.5	1,786	27	26	255	4	1,515 (730-7,042)	1.2
Elinor '96	50 min.	933	938	2,665.0	566	17	5	133	6	355 (185-1,150)	1.6
Hilda '97	50 min.	337	290	717.0	231	11	11	54	3	163 (71-1,088)	1.4
May '96	50 min.	301	72	253.0	13	2	13	92	31	6 (4-10)	2.1
Rock Is. '96	50 min.	2,078	501	1,619.5	341	61	14	24	14	107 (57-241)	3.2
Pinehurst '00	50 min.	4,070	1,572	6,330.0	4,870	435	18	282	63	2,108 (1,625-2,861)	2.3
Beaver '98	50 min.	3,310	2,037	6,427.0	4,526	74	29	522	4	8,498 (4,114-38,681)	0.5
Beaver '00	50 min.	3,310	1,278	4,005.0	3,120	42	20	264	8	1,355 (760-3,563)	2.3
Totals (or means)			46,530	144,567	64,121	8,283	15.6	3,988	690	38,611	2.2

[a] protected slot, all length limits in cm total length

[b] for estimating PL caught , LL kept was increased by 10% to account for released, legal-length walleyes

[c] number of dates that test fisheries were held during the angling season; not a measure of fishing effort

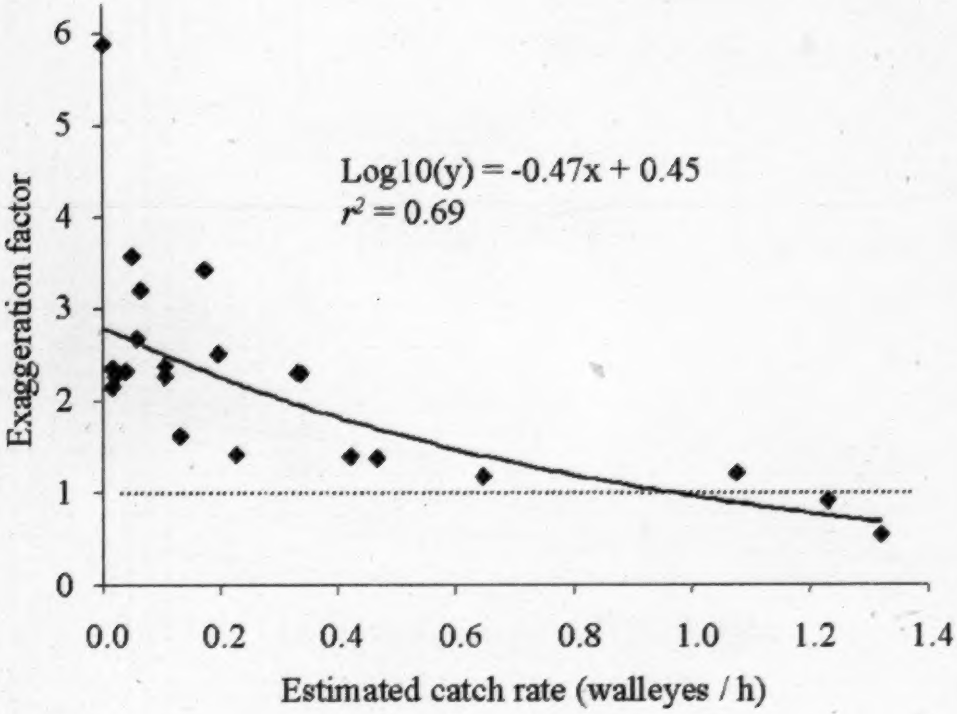

Figure 1. Estimated catch rate for protected-length walleye versus exaggeration factor for 22 Alberta angler surveys in 1991-2000. Dashed line indicates an exaggeration factor of 1 (e.g., estimated catch rate = reported catch rate). Score test for nonconstant variance of residuals, *f* = 0.36, df = 1, 20, *P* = 0.55 (Weisberg 1985).

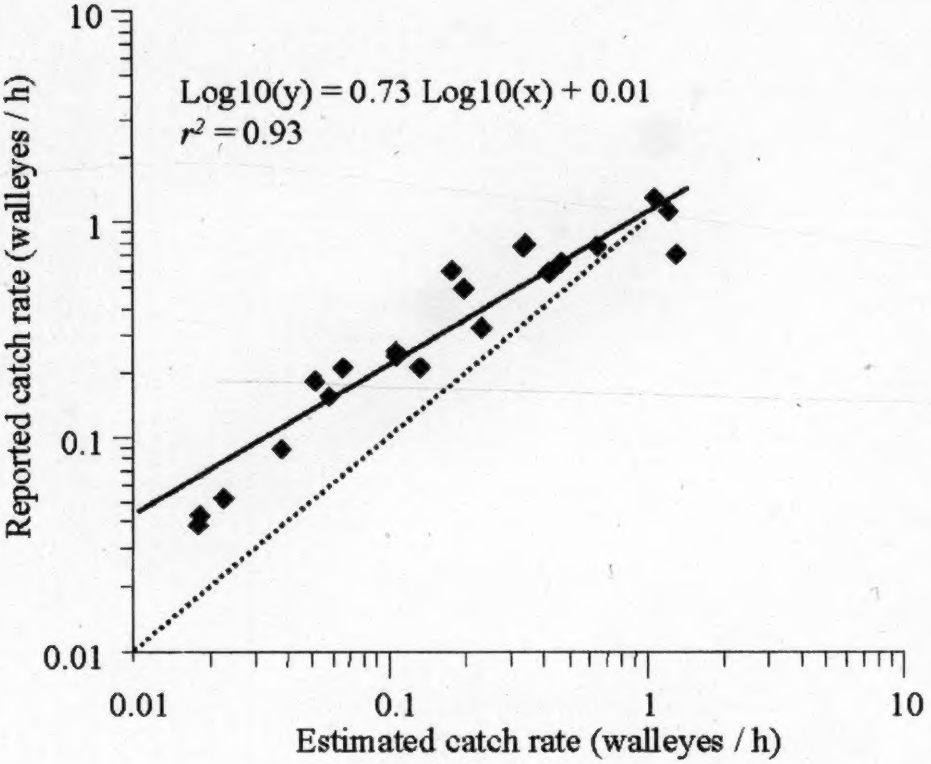

Figure 2. Estimated catch rate versus reported catch rate for protected-length walleye for 22 Alberta angler surveys in 1991-2000. Dashed line indicates that estimated catch rate = reported catch rate. Score test for nonconstant variance of residuals, $f = 0.35$, df = 1, 20, $P = 0.56$ (Weisberg 1985).

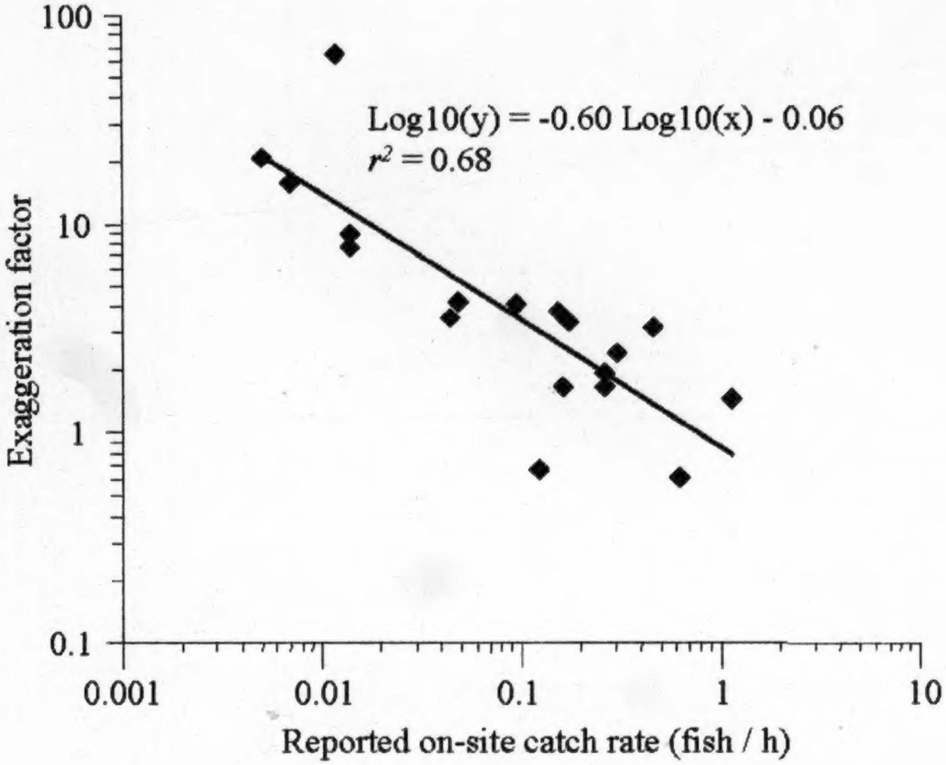

Figure 3. Catch rate reported by anglers during on-site surveys versus exaggeration factor in mail surveys (ratio of mail survey catch rate to on-site catch rate) for salmonid fisheries in Maine. Data from Roach et al. (1999). Score test for nonconstant variance of residuals, $f = 0.11$, df = 1, 16, $P = 0.74$ (Weisberg 1985).

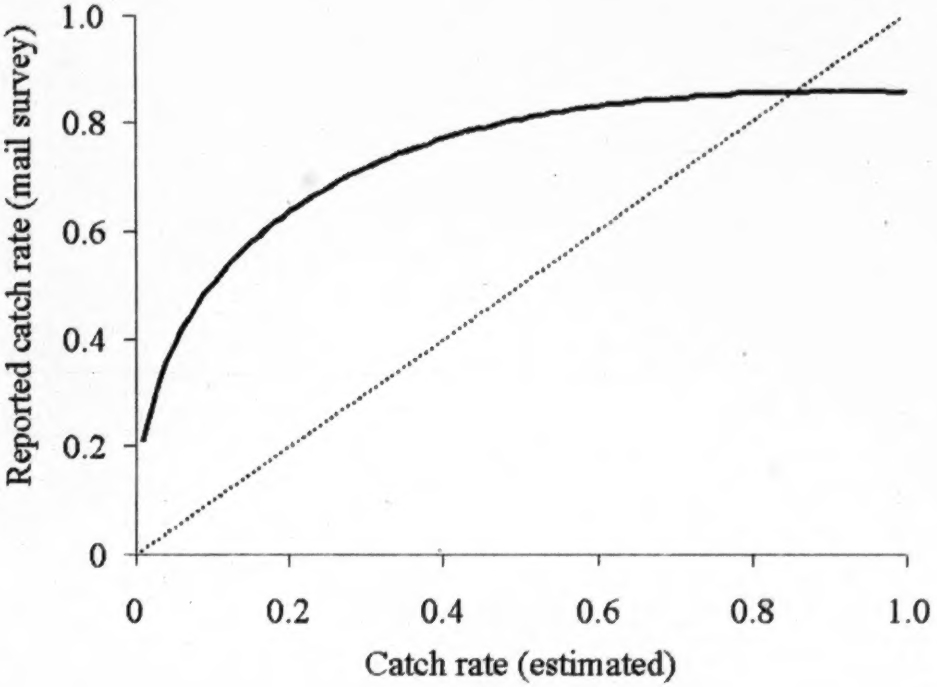

Figure 4. Integration of two levels of angler exaggeration: estimated catch rate as exaggerated in on-site surveys (from this study) and on-site catch rate as exaggerated in mail surveys (derived from data from Roach et al. 1999), showing perceived hyperstability in reported catch rate. Solid line is integrated relationship of estimated catch rate exaggerated in mail surveys, and dashed line indicates that estimated catch rate = mail survey catch rate.

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Chapter 4. Do Anglers' Walleye and Pike Shrink?

Sullivan, M. G. 2002. Do anglers' walleye and pike shrink? Alberta Fish and Wildlife Occasional Fisheries Research Paper.

Abstract.— Anglers apprehended with fish shorter than a minimum length limit commonly argue to enforcement officers that “It must have shrunk.” In designing length limits, biologists often measure live fish (e.g., fish caught by electrofishing or trap-netting) and assume that these measurements are no different from those of dead, harvested fish. To test the biological validity of these arguments, I measured 25 walleye *Sander vitreus* and 13 northern pike *Esox lucius* while alive, and then at timed intervals up to three hours after their deaths. Although measurement variance was large, repeated measures analysis of variance tests showed a statistically significant expansion of walleye after death (2.3 mm) and significant shrinkage of pike (1.7 mm). These changes in length are not large enough to be of concern for most management or enforcement purposes.

Introduction

Consistent measurements of dead and live sport fish are of concern to anglers, enforcement officers and fisheries managers. Length limits are widely used for managing walleye *Sander vitreus* and pike *Esox lucius* sport fisheries in many jurisdictions (Brousseau and Armstrong 1987; Barnhart 1989; Paukert et al. 2001), including Alberta. Enforcement officers commonly hear the following excuse from anglers caught with undersized fish; "It was legal when I killed it. It must have shrunk." Some officers accept this argument and allow anglers up to 2.5 cm for shrinkage, whereas others have a "zero tolerance" policy for undersized fish. Behnke (1989) states that the most important attribute of a management agency is its credibility, yet this inconsistency annoys anglers and damages the integrity of the organization. Should enforcement officers allow for a standard and justifiable buffer zone of fish shrinkage? If so, in their analyses and design of regulations, should fisheries managers then also account for these changes in length?

The topic of changes in fish length following death has received considerable attention by fisheries scientists, but has almost exclusively focussed on shrinkage in larval fishes, which can be a result of chemical preservative (Parker 1963; Cunningham et al. 2000), freezing (Jones and Green 1977; Fowler and Smith 1983), or death (Shetter 1936; Jennings 1991). Shrinkage is not universal, however, as some species have been found to expand after death (Stobo 1972) and in preservatives (Billy 1982). Changes in size are generally attributed to osmotic processes (Hay 1982) in these very small fishes (usually < 1 cm in length). The few studies of larger fish have involved marine fishes kept on ice in ships' holds (Lux 1960; Rice et al. 1989). In most sport fisheries, the species and sizes of fish caught, and anglers' handling of their catch are different from those presently in the literature, and therefore, meaningful extrapolation is unreasonable.

In Alberta, biologists analyze data that encompasses lengths of both live and dead fish. In particular, comparisons of these data are central to estimates of illegal harvest and exaggeration (Sullivan 2002, 2003). Typically, nonlethal capture methods such as trap-netting, electrofishing, and angling are used by biologists because Alberta's sport fish stocks are often overfished, and any additional harvest is undesirable (Post et al. 2001). Fish caught by these means are measured alive. Those collected using lethal capture methods (e.g., gill-netting and trawling) and those sampled from anglers' creels and commercial nets are usually measured dead. To determine whether the lengths of fish while alive differ significantly from the lengths following death, I measured walleye and pike (of lengths typically caught by Alberta anglers) while alive and at timed intervals after death, killing and handling these fish as do anglers in Alberta.

Methods

In May 2000, at Siebert Lake, Alberta, 25 walleye were captured by electrofishing at night and then individually tagged with Floy tags and placed in live-pens. The following day, I dipnetted these fish from their pens, measured them to the nearest millimeter of fork length with a standard fish-measuring board, and killed them with a sharp blow to the head. I placed the carcasses in a plastic fish tub which was stored in partial shade. No ice was added, consistent with Alberta anglers' handling of fish. At timed intervals (5 min, 10 min, 20 min, 40 min, 1 h, 2 h, and 3 h), I removed each dead walleye from the fish tub and measured it. Northern pike were handled similarly, although they were captured using trap-nets at Lac Ste. Anne, Alberta in May 2001. Both study days were sunny, and air temperatures ranged from 15^0C to 18^0C. Water temperatures varied between 7^0C and 9^0C. SPSS (SPSS Inc. 1997) was used for the statistical analyses.

Results

The average fork length of the 25 live walleye examined was 415.9 mm (range = 358–497 mm). For the 13 live pike caught, the average fork length was 544.0 mm (range = 491–604 mm). Dead walleye increased in length (repeated measures analysis of variance, RM ANOVA, *F*

= 7.04, df = 24, $P < 0.001$; Figure 1) and dead pike decreased in length (RM ANOVA, $F = 7.26$, df = 12, $P < 0.001$; Figure 1). After three hours, walleye length had increased, on average, by 2.3 mm (paired t-test, $t = -2.998$, df = 24, $P = 0.006$), and pike length had decreased by 1.7 mm (paired t-test, $t = 3.23$, df = 12, $P = 0.007$). These values represent average length changes of +0.5% in walleye and – 0.3% in pike. Changes in length were not consistent within each species, 7 of 25 walleye shrinking and 3 of 13 pike increasing in length after three hours (Figure 2). The average measurement variation was nearly as large as the time-after-death effects. The mean absolute residual value of all measurements regressed to time was 1.7 mm for walleye (SD = 1.6 mm, n = 200) and 1.4 mm for pike (SD = 1.0 mm, n = 104). There was no correlation between the initial size of walleye and their change in length ($r^2 = 0.00$, $F = 0.08$, $P = 0.78$; Figure 2). For pike, however, there was a significant correlation, smaller pike shrinking slightly and larger pike maintaining their length ($r^2 = 0.30$, $F = 6.11$, $P = 0.03$; Figure 2).

Discussion

Shrinkage of walleye and pike after death was not significant enough to be of concern for fisheries regulation design and enforcement. There is only a slight possibility of a legal-length walleye shrinking to become of protected-length size and therefore becoming illegal. Many officers in Alberta allow anglers up to a 2.5 cm margin of error for undersized fish (although a few officers adopt a zero-tolerance policy for size-limit violations). This margin is excessive to account for inconsistent walleye shrinkage (i.e., the maximum shrinkage seen in a sample of 25 walleye was 0.5 cm). Pike did consistently shrink after death, but by less than 0.2 cm, on average. As the length-limit regulations in Alberta are defined in centimeters, these miniscule changes in length are too small to affect length-limit regulations.

Such minor length changes may be a result of muscle relaxation, measurement error or both. Most of the increase in walleye length occurred within the first 20 minutes after death. Live walleye were firm, perhaps from contracting their body muscles and erecting their spines in defense. Soon after death, walleye became more flaccid, as these muscles relaxed; this may explain the slight increase in length. For pike, length did not change consistently with time. Pike were more difficult to accurately measure than were walleye because pike vigorously flexed their bodies while alive, and after death, tended to curve and stiffen.

The importance of this work was emphasized in 2001 when I was involved in two court cases in Alberta, in which anglers apprehended with protected-length walleye initially told the investigating officers that their fish had shrunk. All disputed-length walleye were smaller than the length limit by more than 2.0 cm. In both cases, at pretrial meetings the anglers changed their pleas from "not guilty" to "guilty" when confronted with Figures 1 and 2, suggesting that their initial defenses (i.e., "My walleye must have shrunk.") were, perhaps, made in error.

Shetter (1936) concluded that the fish shrinkage he documented has a bearing on legislation and enforcement. He studied shrinkage, however, in very small brook trout *Salvelinus fontinalis*, with an average length of only 5.38 inches (13.7 cm). They shrank an average of 0.14 inches (0.4 cm), three hours after death. My findings suggest that for walleye and pike, fish much larger than those studied by Shetter (1936), changes in length after death are insignificant to biologists and enforcement officers. For walleye, enforcement officers and fisheries managers could justifiably implement a zero-tolerance policy for anglers' claims of fish shrinkage. For pike, a "warning zone" of 0.2 - 0.5 cm would accommodate any shrinkage. Fisheries resource agencies using length limits for management purposes should also acknowledge measurement error as a source of variance, made either by officers or by anglers using reasonable care. For example, one might consider issuing warning tickets to rather than imposing fines on anglers in possession of walleye or pike that are 0.5 cm less than a minimum-length limit. This is both an ethical and legal decision that should be applied consistently to avoid loss of agency credibility.

Different fish handling conditions could alter these conclusions. For example, gutting a fish and allowing the carcass to dry in the sun could, presumably, result in shrinkage. Much longer time-after-death periods (e.g., overnight), freezing, or salting fish may alter their length. My study was designed to duplicate those conditions commonly seen by biologists and officers involving anglers at walleye and pike sport fisheries in Alberta. Fish handling conditions in other jurisdictions must be considered before broadly applying these recommendations. Different species of fish may also react differently; therefore, these data may not be applicable to other species (Jennings 1991; Fisher et al. 1998).

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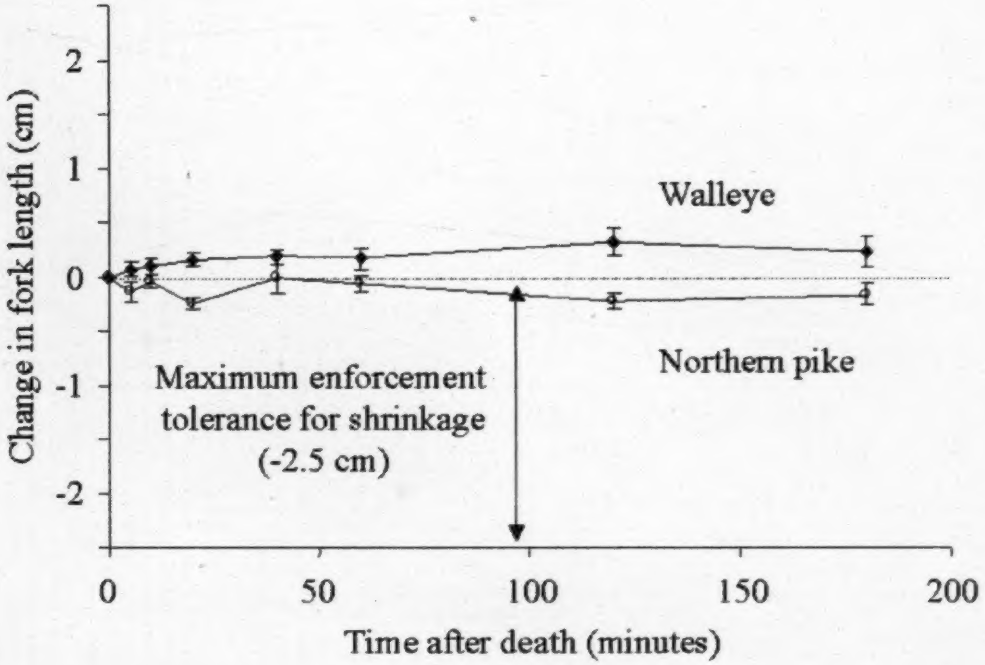

Figure 1. Change in mean fork length of 25 walleye and 13 northern pike after death. Error bars depict 95% confidence limits.

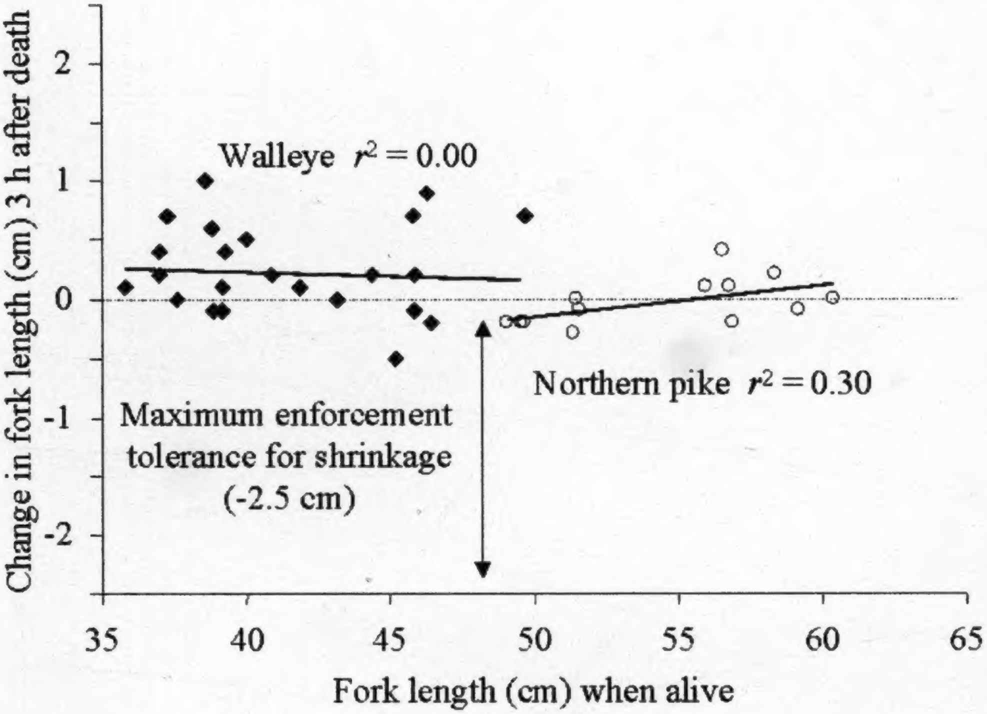

Figure 2. Change in fork lengths of 25 walleye and 13 northern pike three hours after death, in relation to the fishes' initial size.

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Chapter 5. Ecosystem changes associated with depensatory effects of overfishing of walleye *Sander vitreus* in Alberta

Abstract.—Heavy fishing pressure in Alberta's low productivity lakes has resulted in drastic declines in walleye *Sander vitreus* populations within the last 60 years. This decrease was correlated with an increase in numbers of forage fish, primarily spottail shiners *Notropis hudsonius*, with relative densities of shiners at collapsed lakes 5 to 8 times higher than densities at stable walleye lakes. Laboratory experiments showed that these forage fish could consume large numbers of walleye fry. Quantitative modelling based on field and laboratory data indicated that as walleye abundance declines to a critical threshold of 0.3 to 3 adult walleye/ha, increasing densities of forage fish can cause walleye recruitment failures by consuming entire year-classes of walleye fry. Landscape-scale changes observed in Alberta corroborate the hypothesis that this depensatory effect of overfishing may result in altered ecosystems that are resistant to fishery recover efforts, with avian piscivores (e.g., double-crested cormorants *Phalacrocorax auritus*, white pelicans *Pelecanus erythrorhynchos*, and common loons *Gavia immer*) replacing walleye as apex aquatic predators. Fisheries managers must recognize overfishing thresholds for this depensatory ecological effect and avoid reducing fish populations to these levels.

Introduction

Overfishing is a recurring, common problem, with examples ranging from collapses of global-scale commercial fisheries, such as large Pacific tunas *Thunnus* spp. (Cox 2002) and Atlantic cod *Gadus morhua* (Hutchings 1996; Myers et al. 1996) to collapses of smaller-scale recreational and subsistence fisheries, such as lake trout *Salvelinus namaycush* (Evans and Willox 1991) and lake sturgeon *Acipenser fulvescens* (Houston 1987). Immediate economic and social effects of overfishing are readily apparent (Pearse 1988; Smith 1994; Nikiforuk 2002), but the less-apparent ecological consequences may be of equally grave importance (Pauly et al. 1998; Pitcher 2001).

One important ecological consequence of overfishing involves the process of trophic cascades (Carpenter and Kitchell 1985; Kitchell 1992). Sport fisheries often target the large-bodied, apex predators in aquatic systems, such as basses (*Micropterus* spp.), chars (*Salvelinus* spp.) and perches (Percidae), which are usually the slowest-growing and latest-maturing fishes in communities, and are therefore most vulnerable to overexploitation (Cushing 1981). Declines in the abundance of these predators results in increases in abundance of forage fishes, with a cascade of alternating increases and decreases in predation-induced abundance on progressively lower trophic levels (Shapiro 1995). A complex aspect these cascading changes is predator-prey role reversal (Barkai and McQuaid 1988; Post and Rudstam 1992), where forage fish, released from predation pressure, become abundant enough to prey on or compete with the young of the once-dominant apex predator. The original structure and stability of the unfished aquatic community is therefore dependant on the "cultivation" effect of the apex predator maintaining relatively low abundance of the potentially predatory forage fishes (Walters and Kitchell 2001). Loss of the cultivation effect through overfishing results in a depensatory (i.e., declines in fish abundance create conditions enhancing further declines) cycle of increasing forage fish abundance and predation, reduced recruitment of the apex predator, and thereby increased vulnerability to continued overfishing. The consequence of depensatory overfishing and ecological change is the creation of a new and stable aquatic community which has lost the native apex predator, resists recovery, yet has an unexploited niche (i.e., abundant forage fish) for a new apex predator.

Cultivation and depensation effects of overfishing may be widespread (Jackson et al. 2001; Walters and Kitchell 2001), but ecological effects are seldom quantified in traditional, single-species approaches to fisheries management (Link 2002a). Estimating "safe" harvest levels based on single-species assessments, such as maximum sustained yield or yield-per-recruit models (Ricker 1958; Cushing 1981), ignores the interplay of complex community dynamics and confounds effective fisheries management (Hilborn and Walters 1992; Ludwig et al. 1993; Bax 1998). Depensatory community changes may explain the failure of fish stocks to recover in spite of restrictions on fishing (e.g., blue pike *Sander vitreus glaucum*, Nepszy 1977, and walleye *Sander vitreus*, Mrozinski et al. 1991) or extensive re-stocking programs (e.g., walleye, Laarman 1978; Ellison and Franzin 1992, and lake trout, Evans and Willox 1991). This may also partially explain the susceptibility of overfished ecosystems to the rapid invasion by exotic or previously rare species, such the myriad invasions of exotic species in the Great Lakes (Mills et al. 1994) and increases in double-crested cormorants *Phalacrocorax auritus* at heavily-fished lakes in North America (Hobson et al. 1989; Weseloh et al. 1995). Understanding and assessing ecological consequences as risks of overfishing is considered to be a major new requirement for effective fisheries management (Pitcher 2001; Walters and Kitchell 2001; Link 2002b).

The objective of this paper is to demonstrate ecological effects of overfishing on walleye populations in Alberta and to quantify the threshold of critical population size where depensatory effects may be invoked. I conducted field studies to determine the relationship between densities of walleye and forage fish, and laboratory studies to estimate predation rates of forage fish on walleye fry. From this information, I quantitatively modelled the relationship between walleye density and relative effect of forage fish predation on walleye fry, identifying the threshold for the loss of the cultivation effect. I hypothesize that this depensatory relationship may partially explain the landscape-scale, low abundance of walleye and increase in piscivorous birds observed in Alberta. The objective of this paper serves two purposes; as a broad goal, to increase the understanding of (and aversion to) ecological consequences of overfishing; and, as a specific goal, to define a quantitative threshold to recruitment overfishing.

Study Area: Description and Fisheries History

Alberta is a large (661,000 km^2) western Canadian province, yet has few lakes (approximately 800) and fishes compared to the tens of thousands of lakes and high fish diversity in other Canadian provinces. A short post-glacial history of about 9000 years and the long distance from major glacial refugia has resulted in a low diversity of fishes, with approximately 52 native species (Nelson and Paetz 1992). Lakes typically support fewer than five species of small "forage" fish (e.g., minnows, perches, sculpins, and sticklebacks), two to four species of larger-bodied planktivores (e.g., whitefish and suckers), and two or three large, predatory species (e.g., walleye, pike, and burbot). Few lakes have salmonids (e.g., trout or char) and none have centrachids (e.g., basses and sunfishes are not native to Alberta). This is very different from lakes in eastern Canada or the midwest United States, where even small lakes may support over 30 species of fishes (Kempinger and Carline 1977; Becker 1983).

The majority of Alberta's lakes are in the boreal forest ecozone, between 54^{0} and 60^{0} N latitude. Ice-cover occurs for seven months (November to May), with summer water temperatures seldom exceeding 20°C. Air temperatures average $^{-}2^{0}$C to 2^{0}C annually. Growing degree-days (GDD5^{0}C) (i.e., the annual sum of mean daily temperatures greater than 5^{0}C) range from 900 to 1400 for terrestrial sites in northern Alberta. Winterkill is common in lakes smaller than 200 ha, and many lakes are anoxic below the thermocline (Mitchell and Prepas 1990). These climatic factors result in slow-growing and late-maturing fishes (e.g., walleye are sexually mature at ages 8 to 20 years, Sullivan 2003) with low annual fisheries productivity (i.e., total annual yields of all sport and commercially harvested species seldom exceeds 10 kg/ha, with walleye yields of less than 1 kg/ha, Scott 1978).

The low diversity and productivity of Alberta's fisheries makes them especially vulnerable to overexploitation, yet Alberta has extensive sport and commercial fisheries. Most lakes larger than 200 ha have had a 100-year history of commercial gill-netting, usually targeting lake whitefish *Coregonus clupeaformis*, but with by-catches of walleye and northern pike *Esox lucius*. Sport fishing is popular (approximately 4 million angler-days annually, Berry 1995a), with virtually all lakes having easy road access. With few lakes and a large number of licensed anglers, Alberta has a highly disproportionate ratio of anglers to lakes compared to other Canadian provinces (Table 1). The result of this imbalance between fisheries productivity and pressure has been major declines in commercial catches and quality of sport fishing. Records from the fur trade era suggest some fisheries in western Canada were already declining by the late 1800s (Belanger 1895; Tough 1999). Lake trout, once described as widespread in most large Alberta lakes (Chambers 1914), are presently found only in a few scattered localities (Nelson and Paetz 1992). Angler and commercial fishermen reported large decreases in the quality of most fisheries during the 1930s to the 1970s (Chipeniuk 1975). Commercial landings of walleye in Alberta decreased over 85% from the 1940s to the 1970s (Scott 1978). By the 1990s, most sport fisheries for walleye had collapsed and the quality of northern pike fisheries was very low (Ryerson and Sullivan 1998; Post et al. 2002). Although unfortunate for fishermen, Alberta's conditions of low biological productivity and extensive fishing pressure provide biologists with a good opportunity for studying the ecological effects of overfishing in a landscape-scale freshwater ecosystem.

Methods

Consumption of walleye fry by forage fishes (laboratory studies)

During May and June 1995, feeding trials were conducted at aquarium facilities at the University of Lethbridge. Forage fish (yearling spottail shiners *Notropis hudsonius* and yellow perch *Perca flavescens*) were captured at nearby natural ponds and walleye fry (originating from Primrose Lake, Saskatchewan) were obtained from the Cold Lake Fish Hatchery as 3-day old fry. One forage fish (starved for 24 h) and 25 walleye fry were put in a 50 L tank (dark green plastic with convoluted walls). The forage fish was removed after approximately 11 hrs and the remaining walleye fry were counted. Specific times for each trial were recorded. Consumption percentage was calculated as the number of walleye fry remaining alive divided by the number of fry initially placed in the tank (minus any fry found dead on the tank bottom). Consumption rate was calculated as the number of fry consumed divided by the number of hours of each trial. At the end of each trial, the forage fish was euthanised (using a mild carbon dioxide solution) and biological data was collected (i.e., age, fork length, sex, and stomach contents). Fork lengths and largest dorso-ventral body heights (to the nearest 0.1 mm) of walleye fry were recorded on each day of feeding trials using dial calipers. Gape sizes of forage fishes were measured with dial calipers to the nearest 0.1mm. Daytime (0800 - 2000 hrs) and nighttime (2000 - 0800 hrs) trials were conducted. Daytime trials were conducted with natural lighting (e.g., windows in the laboratory). Nighttime trials were conducted with shaded windows and very faint natural light. During the feeding trials at the University of Lethbridge, only young walleye fry (i.e., 3 to 8 days of age) were used because of the difficulty in maintaining large numbers of older fry. Feeding trials using older walleye fry (i.e., 3 to 15 days of age) were repeated at the Cold Lake Fish Hatchery (CLFH) during June 1996. These trials were conducted with yellow perch and additional species of forage fish (yearling ninespine sticklebacks *Pungitius pungitius* and fathead minnows *Pimephales promelas*), but did not include spottail shiners (as this species was not available near the CLFH facilities).

Density of forage fishes and walleye at walleye spawning areas (field studies)

From mid-May to mid-June of 1996 and 1997, seine hauls were conducted at known walleye spawning streams at eight lakes in Alberta (four lakes with collapsed walleye stocks and four lakes with healthy walleye stocks). Field studies were conducted for 10 days at each study site during 1996 and 16 days during 1997. Seine hauls were conducted 8 to 12 times each night at each study stream. Two seine haul sites were selected at each stream. Sites were located between the mouth of the stream and downstream of the walleye spawning beds and were selected for being relatively level, free from large debris, and safe for nighttime wading work in flowing water. Total surface areas of each study site (i.e., surface area of stream between walleye spawning bed and stream mouth) were determined using satellite photography – based GIS analysis of stream length and field estimates of stream width. Seine hauls were conducted at two-hour intervals, beginning at 20:00 (i.e., hauls at 20:00, 22:00, 24:00, and 02:00). Sunset was at approximately 22:00. Seine dimensions were 10 m x 1 m, with 7 mm stretched nylon mesh. Each haul covered a linear distance of approximately 25 m. The surface area of stream sampled was estimated and recorded for each seine haul. The species and numbers of fish captured were recorded. Densities of forage fishes for each study lake were calculated as the means of the total number caught/total area sampled/night, with empirical 95% confidence limits determined from bootstrapped distributions (n = 2000) of the nightly means. Bootstrapping procedures followed Haddon (2001), using MS Excel (Version SR-2). Numbers of forage fish at each spawning stream were estimated as the product of the stream surface area and the density of forage fish. Subsamples of forage fish were collected for analysis of stomach contents. Flow rate information for rivers in each study area was obtained from Alberta Environment or Environment Canada hydrological monitoring stations.

The angling catch rate for walleye was determined at each lake through on-site, summer-season creel surveys. Catch rate was calculated as the number of walleye reported caught/the number of hours reported fished. Walleye caught by anglers in Alberta are usually age 3 and older (30 cm total length and larger), therefore these catch rates do not include small, juvenile walleye. Walleye density at the study lakes was calculated as a function of angling CPUE using:

Adult walleye/ha = 33.3 (angling CPUE) + 0.7, $r^2 = 0.99$, n = 7 fisheries, $P < 0.01$ (Alberta Fish and Wildlife Division, unpublished data). The classification of each walleye fishery (i.e., stable, vulnerable, or collapsed) follows Berry (1995b) and the Alberta Guide to Sportfishing Regulations (1996).

Landscape-level changes in walleye and birds

Long-term trends in walleye populations were inferred from annual commercial fishing records (Scott 1978) and Alberta Fish and Wildlife file data. Piscivorous bird data was obtained from Alberta Fish and Wildlife Division and Parks Canada (Wood Buffalo) file data.

Quantitative modelling of walleye and forage fish

I developed a static, deterministic simulation model (using MS Excel, version SR-2) to estimate the potential effect that predation by forage fish may have on recruitment of walleye fry (Figure 1). This model calculated annual fry production from a theoretical walleye population, simulated using a 3000 ha lake with a single spawning stream of 3 km long and 50 m wide. Walleye density in the model was varied deterministically from 0.1 to 40 walleye/ha of lake area (with demographic proportions of 60% immature, 25% males and 15% females, Alberta Fish and Wildlife Division file data), and was independent of recruitment success. Egg production was calculated from the number of female walleye and a simple linear relationship of fecundity and average female body weight. Body weight declined from 2 kg to 1 kg over the range of walleye densities, to account for growth overfishing. Relative fecundity was 40,000 eggs/kg of body weight, determined from Baccante and Colby (1996), using a typical Alberta lake GDD of 1200. Fry production was simulated with low (6%), moderate (18%), and high (36%) hatching success (Johnson 1961; Mathias et al. 1992). Density of forage fish was calculated as a function of walleye density using data from the field component of this study. Forage fish predation rates on walleye fry were determined from the laboratory component of this study. Effect of forage fish predation on walleye recruitment was calculated as the number of fry potentially consumed/number of fry produced. Potential consumption could exceed fry production as the model did not limit forage fish abundance or consumption with respect to density of walleye fry.

Results

Consumption of walleye fry by forage fish (laboratory studies)

In total, 163 feeding trials were conducted, with forage fishes eating, on average, 50% of the walleye fry presented to them, with an average consumption rate of 1.1 fry/h (Table 2). Spottail shiners had the highest consumption percentage and rate on young walleye fry (3 to 8 days of age). Consumption percentages and rates were slightly lower during the night than during the day for all species (Table 3). Consumption percentages by three forage fishes declined with increasing age and size of walleye fry (Figure 2). The dorso-ventral body height of walleye fry would exceed the maximum gape size of these forage fishes when fry were 10 to 20 days of age (Figure 3) and predation would likely cease.

Satiation due to stomach fullness likely did not occur at these rates of predation. Stomach analysis showed rapid digestion with a very low probability of observing fry remains in forage fish stomachs after a maximum of 12 hours (Table 4).

Density of forage fishes and walleye at walleye spawning areas (field studies)

In total, 899 seine hauls, covering 43,515 m^2, were conducted near the walleye spawning areas of eight Alberta lakes (Table 5) during 1996 and 1997, capturing 49,840 fish of 16 species (Figure 4). Of these, spottail and emerald shiners *Notropis atherinoides* composed 93% (46,788/49,840) of the fish caught. The average density of shiners seined at the study sites was 1.1 fish/m^2, with shiner densities in each year 5-8 times higher at collapsed walleye lakes than at stable walleye lakes (Table 6). The estimated numbers of shiners in each spawning stream was negatively correlated with the angling catch rate of walleye ($r^2 = 0.58$, df = 7, $P = 0.03$, Figure 5). Relative densities of shiners were lower at all study sites during 1997 compared to 1996 (Figure 6), likely a result of flood conditions (i.e., increased volumes of water diluted the concentration of forage fish). No remains of walleye fry were found in stomach contents of spottail shiners collected from either collapsed lakes (n = 45 dissections) or stable walleye lakes (n = 55 dissections).

Quantitative modelling of walleye and forage fish

The following values derived from laboratory and field studies were used to estimate the relationship between walleye catch rate and potential fry predation (as a percentage of total fry production) by forage fish, as shown in Figure 1.

Forage fish predation rates = 1.1 fry/ h, over 10 days.

Forage fish/m^2 = -2.045 (walleye CPUE) + 3.200 (1996, normal stream flow)

Forage fish/m^2 = -0.258 (walleye CPUE) + 0.378 (1997, flood stream flow)

The model shows a rapid increase in fry predation at densities of 0.3 to 3 walleye/ha (Figure 7). Below these densities, forage fish can potentially consume the entire year-class of walleye fry (i.e., 100% fry consumption is the critical threshold of walleye density). This threshold varied inversely with hatching success (i.e., lower hatching success requires higher critical densities of walleye to prevent year-class loss from predation). High stream flow (assumed to be the cause of lower densities of forage fish during 1997) resulted in a lower critical threshold of walleye density.

Population trends in walleye and piscivourous birds

Commercial catches of walleye declined severely at many Alberta lakes from 1940 to 1970 and remained low. The largest declines generally occurred during the 1940s, with little or no apparent recovery in these catches during the next several decades, in spite of extensive restocking efforts, habitat restoration, and recreational harvest restrictions. Years after the steepest declines in catches, large increases in numbers of white pelicans *Pelecanus* *erythrorhynchos* and double-crested cormorants were observed at northern Alberta breeding colonies from the 1970s to the 1990s (Figure 8). These major changes in populations occurred over a very large geographic area (Figure 9).

Discussion

Ecological Changes

Dynamics of large, complex ecosystems are difficult, if not impossible, to quantitatively assign to causal factors (Schelske and Stoermer 1994; Evans 1994) and my study provides only correlative evidence of a landscape-scale trophic cascade. As a case study, however, overfishing in Alberta involves several predisposing factors that heighten the risk of human-triggered trophic cascades. Unusually high fishing pressure relative to low biological productivity and low diversity of fishes and fishing lakes resulted in intensive fishing even as stocks declined to low levels (Sullivan in press). This not only greatly reduced walleye stocks, but also put heavy fishing pressure on other aquatic predators (e.g., northern pike and large yellow perch), likely further releasing predation pressure on the few species of smaller forage fishes (Kidd et al. 1999). A strong increase in both forage fish and avian predators, as observed in this study of the simple Alberta system, would be expected. These changes would not be expected in more complex ecosystems. In more species-and lake-rich systems, if a fish stock declines from overfishing, anglers may simply move to another lake or focus on another species, thereby avoiding the critical depensation threshold (Walters and Cox 1999). Even with continued fishing pressure in a species-rich system, a less-desirable or less-catchable predatory fish may increase and occupy the vacating niche (Walters and Kitchell 2001). Either response (i.e., angler or species shifts) would avoid initiating the loss of cultivation effects and reduce the risk of cascading trophic changes.

Large-scale ecosystem changes involving fish and birds may have occurred throughout other low productivity ecosystems in response to widespread overfishing. Major reductions of most large, predatory percids and salmonids occurred throughout the Great Lakes area, in large part due to overfishing (Colby et al. 1991, Evans and Willox 1991). Overfishing of large-bodied sport fish appears to be widespread in southern and central Canada (Post et al. 2002). In these same areas, double-crested cormorants have greatly increased (Hanisch 2001). These increases are partially attributed to improved breeding success caused by reductions in pollutants such as DDT (Jackson and Jackson 1995), but are also attributed to increases in forage fish (Hobson et al. 1989; Weseloh et al. 1995). Another avian piscivore, common loons *Gavia immer*, have been increasing in southern Canada (Semenchuk 1992), in spite of concerns about reduced fecundity due to pesticides and mercury (Vogel 1996). High densities of forage fish may allow loons to breed at younger ages and occupy smaller territories, thereby increasing their absolute numbers despite reduced fecundity. For example, at Talbot Lake in Jasper National Park, Canada, heavy fishing pressure on northern pike coincided with the appearance of a dense population of spottail shiners, previously a rare species in the Park (W. Hughson, personal communication). Loons have increased to very high densities on this lake (i.e., 8 breeding pairs and 8 chicks fledged during 2002, on a 340 ha lake) but have remained stable on other Park lakes without coincidental pike declines and shiner increases (Jasper National Park file data). If densities of avian piscivores are unnaturally high as an ecological consequence of overfishing, both fisheries and wildlife biologists should be aware that avian declines may occur if fisheries recover. Spottail and emerald shiners decreased significantly in western Lake Erie when walleye stocks recovered (Knight and Vondracek 1993). Nocera and Burgess (2002) show that because of rigid diving energy budgets, loons have a minimum threshold of prey density, and may react catastrophically to reductions in prey density. Coordinating fishery recovery efforts with wildlife management strategies may be useful, both for scientific efficiency and public relations.

The complexity of these interacting trophic relationships may confound research interpretation. Cascading effects influence many trophic levels, including invertebrates, algae, and nutrient cycles (Carpenter and Kitchell 1985; Shaprio 1995; Madejian et al. 2002). As a result of this multidisciplinary complexity, far-reaching effects of fisheries collapses may not be anticipated or recognized. For example, nutrients transported by migrating salmon have extensive ecological effects on riparian vegetation, invertebrates, and fish production in interior areas far from the source of the nutrients in the Gulf of Alaska (Kline et al. 1993; Larkin and Slaney 1997). In my study, declines in walleye and correlated increases in forage fish occurred over large areas in northern Alberta. Increased abundance of forage fishes likely decreased aquatic invertebrates, which in turn would affect predators such as bats, who feed heavily on aquatic-based invertebrates (Grindal et al. 1999). Bats in Alberta roost in the deeply corrugated bark of old-growth trees, usually in upland sites far from water (Crampton and Barclay 1998). Their nocturnal migration from feeding sites (aquatic) to roosting sites (terrestrial) may be important for nitrogen transport into interior forests (Marcott 1995), a necessary nutrient for maintenance of old-growth forest ecosystems (Stelfox 1995). Fisheries collapses that occurred decades ago may thereby influence areas as seemingly unrelated as bat population dynamics, mushroom growth, or annual allowable cut estimates for forestry companies.

Complexity of trophic relationships may confound management actions. For example, opposum shrimp *Mysis relicta* were introduced to enhance kokanee salmon *Oncorhynchus nerka* in Flathead Lake, Montana but instead competed for cladoceran prey and extirpated the salmon. This unintended trophic cascade collapsed not only an economically important sport fishery, but lead to the closure of a important national park tourist centre, popular for viewing grizzly bears *Ursus arctos* and bald eagles *Haliaeetus leucocephalus* that once fed on the dense shoals of spawning fish (Spencer et al. 1991). Intervention in the changing trophic system described in my Alberta study may have similar unintended consequences. There are widespread proposals to reduce cormorant numbers because of perceived predation on sport fish, both generally in North America (Hanisch 2001) and specifically in northern Alberta. My study suggests that high densities of forage fish may be preventing walleye recovery through the loss of cultivation effects. As predators on forage fish (Derby and Lovvorn 1997; Hanisch 2001; Alberta Fish and

Wildlife file data), cormorants may theoretically be benefiting recovery of walleye by reducing forage fish predation and competition, rather than impeding recovery by directly consuming walleye. Biomanipulation has a long history of unintended consequences (Shapiro 1990; Bodini 2000). In the case of recovering sport fish stocks in Alberta, actively reducing avian predators may do more harm than good and the effects of avian reduction programs should be carefully monitored.

Critical Threshold for Depensatory Response

My simulations showed a rapid increase in predation of walleye fry as densities declined to 0.3 to 3 adult walleye/ha, suggesting that a walleye stock could collapse because of recruitment failure below this critical threshold. This is a very low density, approximately one third of the 25th percentile of densities of North American walleye populations reported by Baccante and Colby (1996). Other researchers have also suggested that predation-induced recruitment failures occur at very low densities of walleye. Walleye stocks in Green Bay (Lake Michigan) were reduced to low densities during the 1960s because of habitat loss and pollution, but even after mitigation for these effects, recovery failed because of predation on larval walleye by introduced alewives *Alosa pseudharengus* and rainbow smelt *Osmerus mordax* (Schneider and Leach 1977). Expanding populations of introduced Pacific salmonids decreased the abundance of alewives and smelt, and walleye recruitment appears to have recovered (Schneider et al. 1991). Jude (1992) suggested that natural recruitment of overfished walleye in the Saginaw River (Lake Huron) failed because of alewive predation on fry. Recovery of the collapsed walleye fishery in Dauphin Lake, Manitoba, was hindered by heavy predation on stocked walleye fry by spottail and emerald shiners (Giles and Foster 1987, Franzin and Harbicht 1992). Density of walleye fry in collapsed populations may be very low (e.g., 0.2 to 1 fry/3500 m^2 in rivers entering Nipigon Bay, Lake Superior, Kelso and Cullis 1996). Densities of forage fish at collapsed walleye lakes in my study (0.3 to 3 fish/m^2) could rapidly consume all fry at these low densities. With high walleye densities (and correspondingly more fry and fewer forage fish), however, depensatory effects would not be expected, as suggested by Schram et al. (1991) based on the coexistence of abundant walleye and smelt stocks in Lake Superior.

The risk of depensatory predation increases with declines in walleye density, but will be affected by the complexity of the trophic interactions of early life history stages. Predators, prey, and competitors may change roles with changes in relative size and density. Yellow perch, acting as either prey or predator, can enhance (Oneida Lake, Forney 1974; Lake Erie, Madenjian et al. 1996), or decrease (Escanaba Lake, Hansen et al. 1998) walleye fry recruitment. Walleye populations showed unpredicted increases and decreases in Ontario lakes following introductions and removals of perch and pike (Kriska et al. 1996). Even-year abundance of *Hexagenia* mayflies may buffer walleye fry against cannibalism and increase recruitment (Ritchie and Colby 1988; Colby and Baccante 1996), but could also act by satiating predatory forage fish and thereby reduce depensatory predation. Selective removal of walleye in Savanne Lake, Ontario coincidentally reduced pike densities, apparently via increased numbers of large yellow perch preying on juvenile northern pike (Spencer et al. 2002). This could intensify depensatory effects by releasing forage fish from predation by two apex predators at once. Because of the complexity and uncertainty of these interactions, the critical threshold quantified in my study should be considered as a level of increasing risk, rather than a limit for sustainable exploitation.

The critical threshold of depensation in my simulations was moderated by water levels (via relative density of forage fishes), similar to empirical evidence from other field studies of water levels affecting recruitment. Nelson and Walburg (1977) found a positive correlation between recruitment of river spawning walleye and volume of spring discharge in Missouri River reservoirs. Thorn (1984) found that high waters during spawning were associated with good walleye reproductive success. Pitlo (2002), however, found no correlation between river discharge and abundance of age-0 walleye in mainstem Mississippi River. High water levels may enhance walleye recruitment by increasing the amount of spawning and rearing habitat, and by increasing food for juvenile walleye (Stone and Lott 2002), but would also decrease depensatory predation. By combining enhanced spawning and decreased fry predation in collapsed populations, flood events could break the cycle of depensatory predation and re-initiate cultivation effects. For example, the walleye fishery in Lesser Slave Lake, Alberta collapsed from overfishing during the 1950s and did not recover until several extremely abundant year-classes were produced in the late 1970s during periods of high stream flows (Mitchell and Prepas 1990).

In my model, risk of depensatory recruitment failure was inversely related to growth rate of walleye fry, with faster-growing fry being vulnerable to predation for a shorter time. Growth of walleye fry is strongly related to temperature (Johnson 1999), which is correlated with walleye recruitment success in many populations (Serns 1982; Madenjian et al. 1996; Hansen et al. 1998, Schupp 2002). Increased growth can improve recruitment success by reducing the period of vulnerability to mortality from spring storms (Busch et al. 1975) and cannibalism (Chevalier 1973). Rapid spring warming would also increase zooplankton abundance and, in theory, reduce fry foraging time in risky areas (Walters and Juanes 1993). Predation on fry may be the proximate mechanism for decreased recruitment ultimately correlated with temperature and growth.

Decreasing the period of vulnerability of stocked walleye fry to predation by forage fish may be an effective strategy to improve stocking success, one of the focal areas of walleye management in North America (Goeman 2002). In spite of decades of intensive effort and coordinated studies, walleye stocking is still usually unsuccessful, with wider variation in success of fry stocking compared to stocking fingerlings (Ellison and Franzin 1992). Because of their larger size and enhanced swimming ability, fingerling walleye would be less vulnerable than fry to predation by forage fish (Colby et al. 1987; Santucci and Wahl 1993). Some jurisdictions, such as Ontario (Kerr et al. 1996) and Illinois (Brooks et al. 2002) recommend stocking fingerlings, rather than fry, but the added expense of rearing fingerlings usually favours fry stockings (Mitzner 2002). Fingerlings are more expensive to stock than fry because of the additional capital and manpower costs of extensive pond-culture, as well as the loss of fingerlings to cannibalism in high-density rearing ponds. Walleye fry are typically stocked at 3 to 6 days of age (6 to 10 mm), while fingerlings are raised to 30 to 50 days (> 50 mm). My study suggests the predator-avoidance benefit of stocking fingerlings may be largely achieved by stocking slightly older fry (15-20 days old), and with the lower cost of fry. This strategy would not work in situations with walleye predators larger than spottail shiners, such as predation on stocked walleye by largemouth bass *Micropterus salmoides* (Brooks et al. 2002) or large alewives (Brooking et al. 1998). Additional strategies to increase stocking success by avoiding forage-fish predation would be to stock fry when alternate prey (i.e., zooplankton) is most abundant (Johnson and Mathias 1994; Brooks et al. 2002). Stocking fry offshore to avoid concentrations of predators, as suggested by Kerr et al. (1996), would also be effective, although this may prevent fry from imprinting on spawning and nursery areas (Jennings et al. 1996). In spite of possible improvements, however, stocking walleye does not reduce risks and consequences of recruitment overfishing. Although stocking has created new self-sustaining walleye fisheries (Kempinger and Carline 1977), it rarely restores collapsed, native populations (Laarman 1978, Li et al. 1996, Eldridge et al. 2002). Despite 20 years of intensive effort, Alberta's extensive walleye stocking program has neither restored collapsed fisheries or created self-sustaining populations.

Conclusions

Overfishing of walleye in Alberta may have caused a series of cascading population changes in both aquatic and terrestrial communities. Simulation modelling suggests that these changes are initiated when the densities of walleye populations reach a critical threshold of 0.3 to 3 adults/ha and the cultivation effects of suppressing forage fish predation on walleye fry are lost, causing recruitment failures and fishery collapses. These fisheries will most likely remain collapsed until the coincidental occurrence of reduced forage fish abundance and high walleye recruitment, perhaps mediated through high stream flows. Intervention in these systems by controlling populations of piscivorous birds may have the unintended consequence of hindering recovery by reducing predation on the predatory forage fish that are the proximate mechanism of the collapse. Conventional walleye stocking methods will probably also fail to recover these fisheries. My primary conclusion reinforces those of Walters and Kitchell (2001) by demonstrating mechanisms, consequences, and critical thresholds for recruitment overfishing. Fisheries managers are thereby cautioned to avoid allowing populations to fall to these critical levels.

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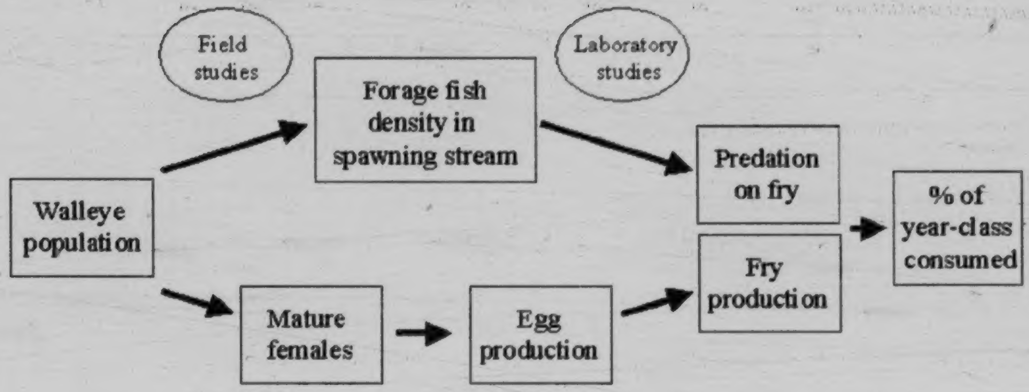
Field studies
Laboratory studies
Forage fish density in spawning stream
Walleye population
Predation on fry
% of year-class consumed
Fry production
Mature females
Egg production

Figure 1. Model of potential effect of forage fish predation on walleye fry production. Relationships between walleye density and forage fish density were derived from field studies, consumption rates on walleye fry were derived from laboratory studies, and walleye egg production parameters were derived from published values.

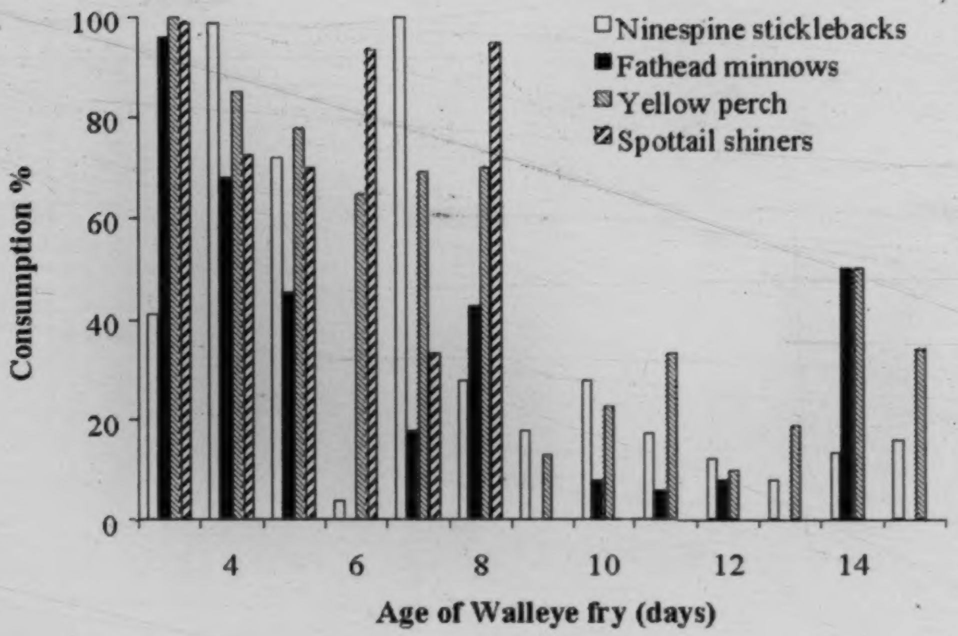

Figure 2. Decline in consumption of walleye fry by forage fish in laboratory feeding trials. Trials were conducted at aquatic facilities at University of Lethbridge during June, 1996 and at the Cold Lake Fish Hatchery during June, 1997. Each trial involved 1 forage fish and 25 walleye fry, with consumption monitored over 12 hours.

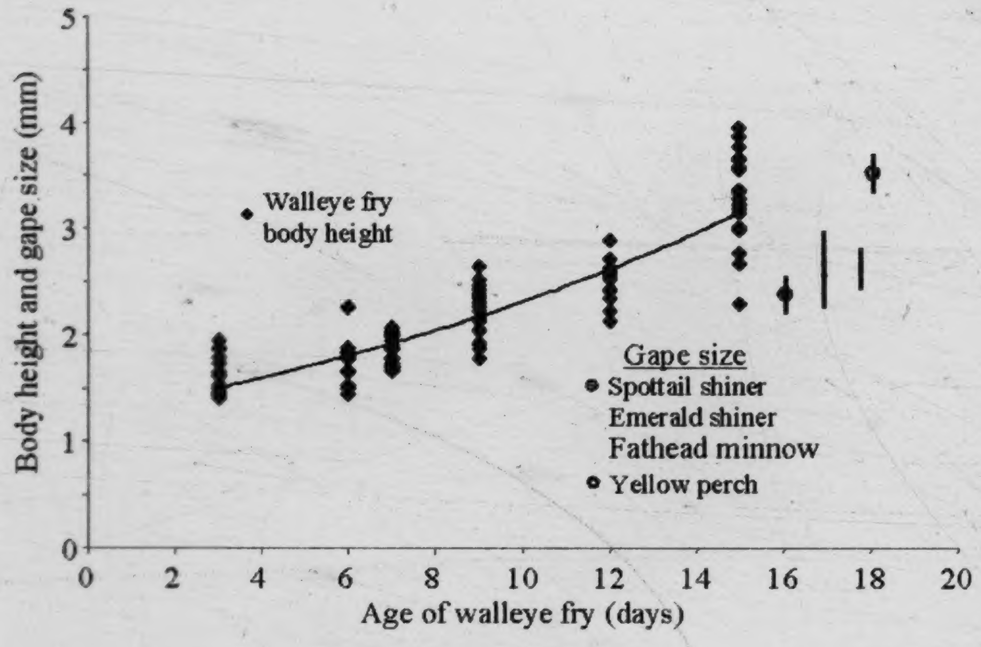

Figure 3. Growth in body height of walleye fry compared to maximum gape size of forage fishes. Walleye fry were collected from rearing ponds at the Cold Lake Fish Hatchery, June1997. Forage fish were collected near the Cold Lake Fish Hatchery, June 1997. Gape sizes are means with bars representing 95% confidence limits (n = 20 forage fish of each species).

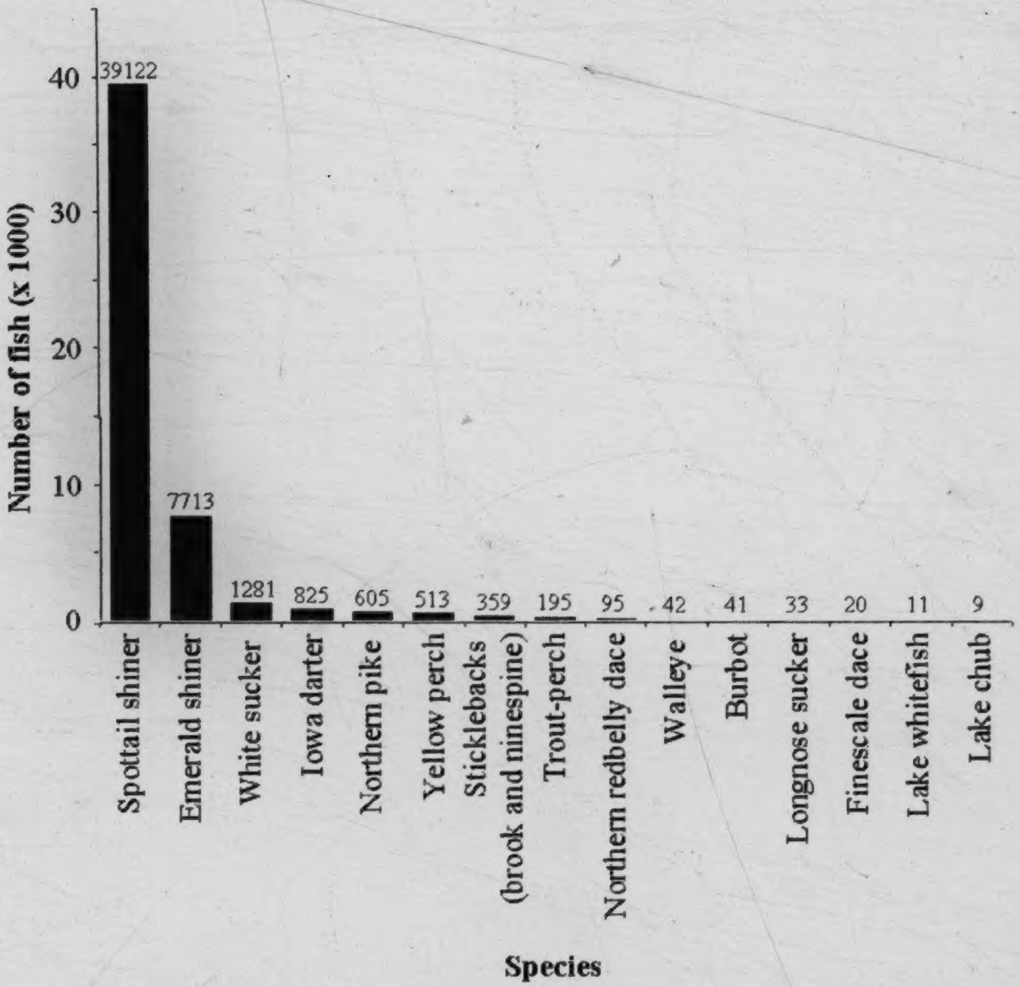

Figure 4. Fish species and numbers caught in 915 seine hauls at eight walleye spawning streams in Alberta during June 1996 and 1997. Seine hauls were conducted from 2 hours before sunset to 4 hours after sunset.

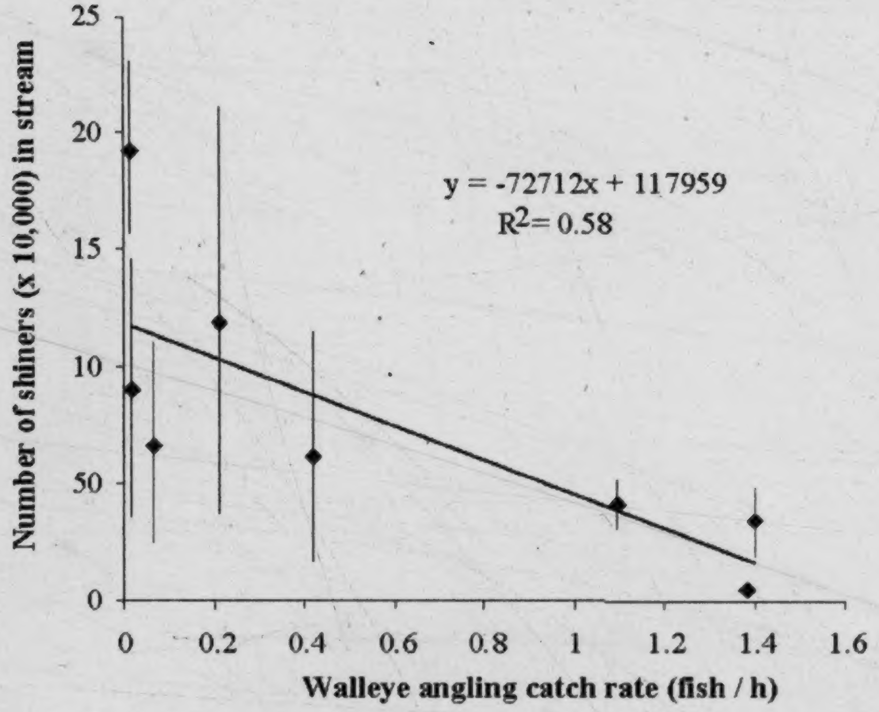

Figure 5. Estimated number of shiners (*Notropis* spp.) at eight Alberta walleye spawning streams compared to summer-season angling catch rate on walleye at lakes during 1996 and 1997. Numbers of shiners were estimated from seine catches per unit area multiplied by the surface area of the stream below known walleye spawning areas. Bars are 95% confidence limits.

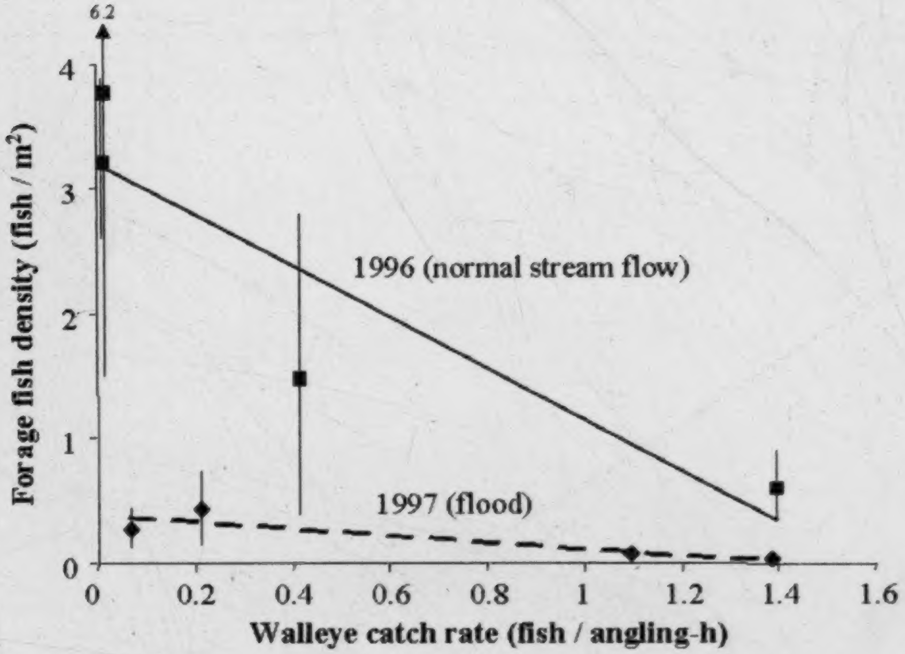

Figure 6. Density of forage fish versus angling catch rate of walleye at 8 Alberta walleye spawning streams during two flow regimes; normal (1996), and flood conditions (1997). Data from 1996; $y = -2.05x + 3.20$, $r^2 = 0.82$, df = 3, $P = 0.09$. Data from 1997; $y = -0.26x + 0.38$, $r^2 = 0.82$, df = 3, $P = 0.09$.

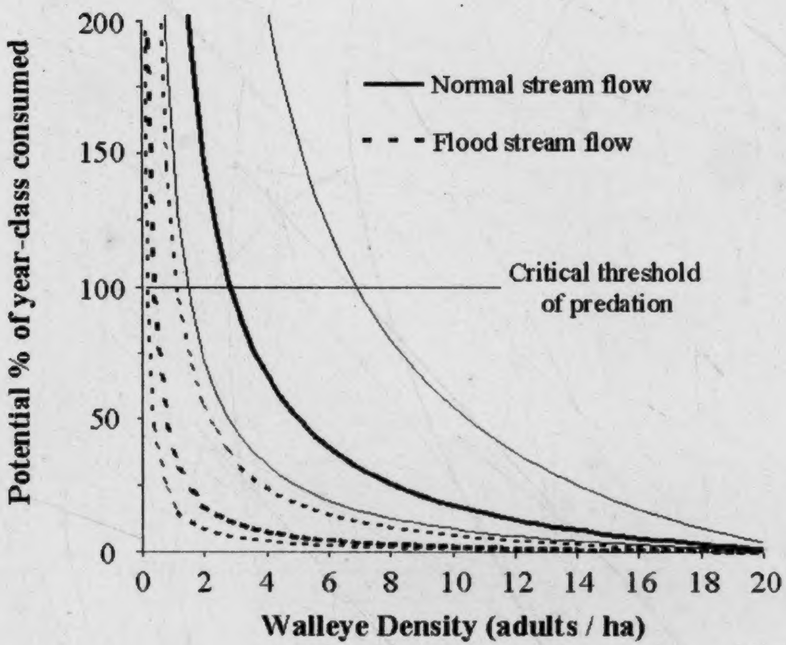

Figure 7. Results of simulation model showing relationship between walleye density and potential predation on walleye fry by forage fishes. Solid lines are results from simulations using shiner–walleye density relationship from 1996 (normal stream flows). Broken lines are results from simulations using shiner–walleye density relationship from 1997 (flood stream flows). Bold lines are results from simulations with average egg–fry survival (18%), and thin lines represent low (6%) and high (36%) egg survival.

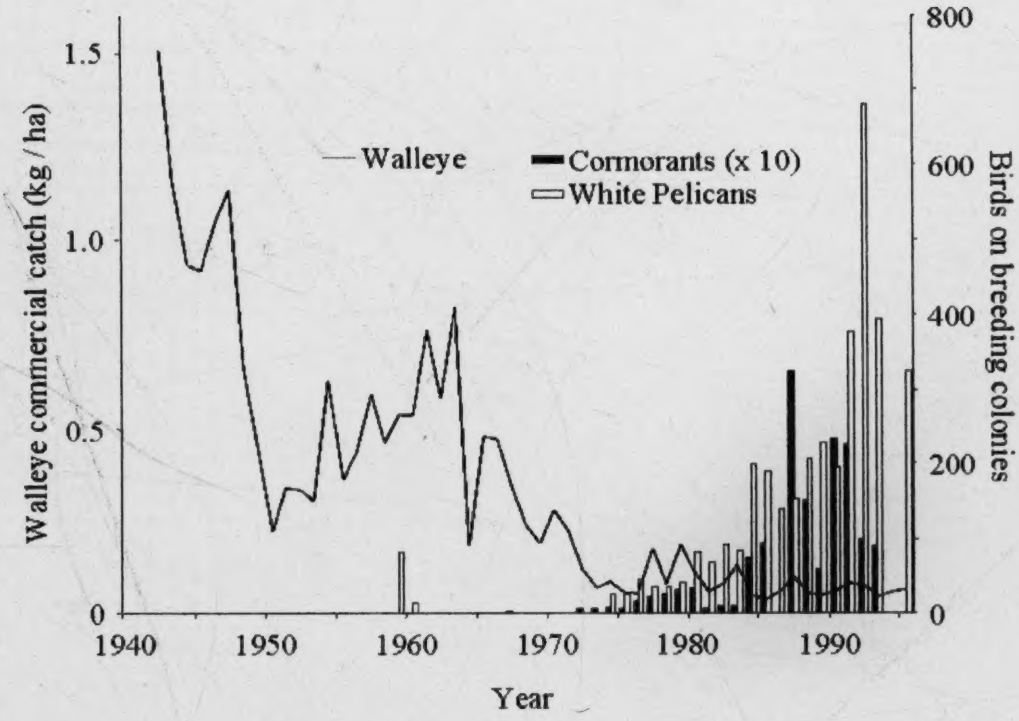

Figure 8. Decline in walleye commercial catches and increase in piscivorous birds in Alberta from 1942 to 1995. Commercial catches are annual averages of catches at La Biche, Calling, Touchwood, Wolf, Beaver, Moose, Ste. Anne, Christina, Winefred, Frog, Amisk and Marie lakes from 1942 to 1995 (data from Scott 1976 and Alberta Fish and Wildlife file data). Piscivorous bird counts are from colonies on the Slave River, and La Biche, Therien, Frog, and Beaverhill lakes during 1959 to 1995 (data from Alberta Fish and Wildlife, and Parks Canada file data).

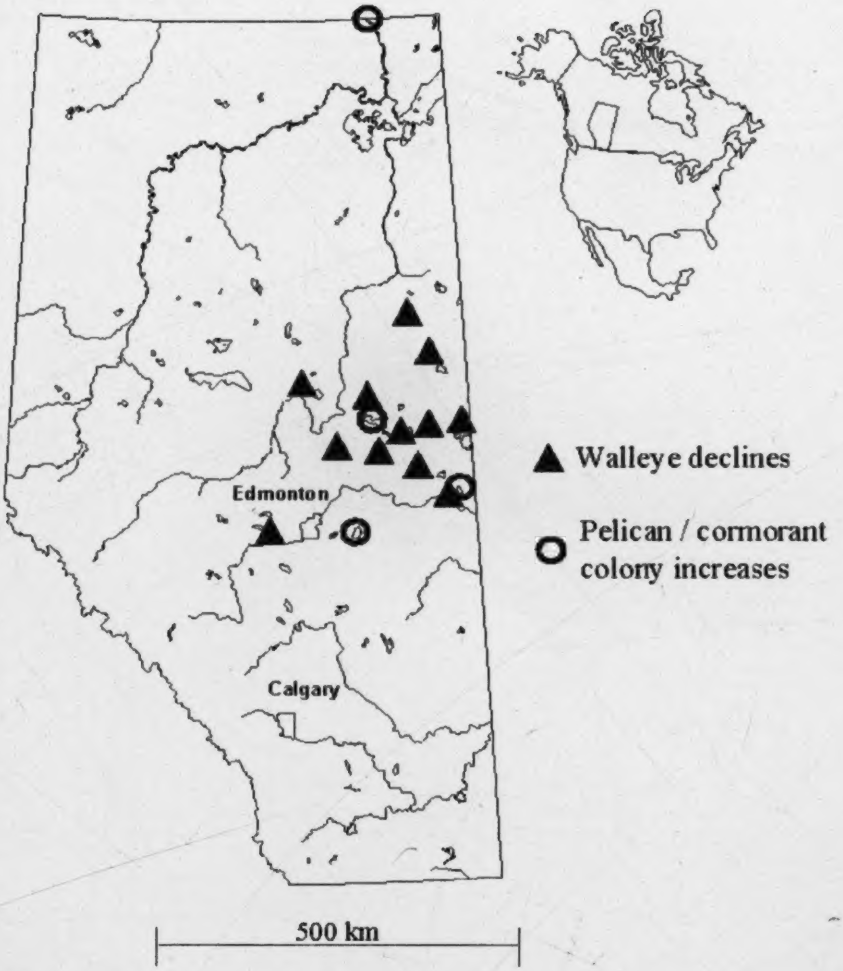
Edmonton
Calgary
▲ Walleye declines
○ Pelican / cormorant colony increases
500 km

Figure 9. Location of walleye declines and piscivorous bird (double-crested cormorant and white pelican) increases in Alberta during 1942 to 1995.

Table 1. Ratio of licenced resident anglers to lakes in four Canadian provinces. Data from provincial tourism bureaus for mid-1990s (from Sullivan in press).

Province	Number of lakes	Number of licenced anglers	Anglers/lake
Alberta	800	250,000	312.5
Saskatchewan	94,000	184,000	2.0
Manitoba	110,000	198,000	1.8
Ontario	250,000	585,000	2.3

Table 2. Consumption of walleye fry (3 to 8 days of age) by forage fishes during laboratory feeding trials, 1996 and 1997. Feeding trials involved 1 forage fish and approximately 25 walleye fry during 12 hours.

Forage fish	Number of feeding trials	% Walleye fry eaten (# eaten/ # available)	Consumption rate (fry/h)
Spottail shiners	36	76% (569/750)	1.6 (569 fry/348 h)
Yellow perch	74	65% (1150/1777)	1.5 (1150 fry/785.75 h)
Ninespine sticklebacks	28	34% (238/700)	0.8 (238 fry/306.25h)
Fathead minnows	25	24% (146/601)	0.5 (146 fry/274.25h)
Totals (or means)	163	50%	1.1

Table 3. Comparison of consumption rates of walleye fry (3 to 8 days of age) by forage fishes during day and night feeding trials, 1996 and 1997. Feeding trials involved 1 forage fish and approximately 25 walleye fry during 12 hours. Percentage fry eaten are number of fry eaten/ number of fry available. Consumption rates are minimum values as forage fishes may not have been satiated.

	Day		Night	
Forage fishes	% fry eaten	Consumption rates (fry/h)	% fry eaten	Consumption rates (fry/h)
Spottail shiners	78% (320/409)	1.7 (320 fry/193 h, 19 trials)	73% (249/341)	1.6 (249 fry/155 h, 17 trials)
Yellow perch	68% (632/913)	1.6 (632 fry/398.75 h, 38 trials)	60% (518/864)	0.9 (518 fry/570 h, 36 trials)
Ninespine sticklebacks	35% (122/350)	0.8 (122 fry/153.25 h, 14 trials)	33% (116/350)	0.8 (116 fry/153 h, 14 trials)
Fathead minnows	29% (90/315)	0.6 (90 fry/142.25 h, 13 trials)	20% (56/286)	0.8 (56 fry/132 h, 12 trials)
Means	53%	1.2	47%	1.0

Table 4. Stomach contents of forage fishes after consuming known quantities of walleye fry within past 12 hours. Feeding trials conducted during 1996 and 1997, each involving 1 forage fish and approximately 25 walleye fry.

Forage fishes	# fry observed in stomach/# walleye fry consumed (%)
Spottail shiners (n = 3)	1/35 (2.9%)
Yellow perch (n = 29)	59/374 (15.8%)
Ninespine sticklebacks (n = 18)	12/219 (5.5%)
Fathead minnows (n = 9)	0/114 (0%)
Totals (n = 59)	72/742 (9.7%)

Table 5. Physical and limnological characteristics of study lakes and spawning streams. Data from Mitchell and Prepas (1990) and Alberta Fish and Wildlife Division file data. n/a – data not available

Lake	Latitude	Longitude	Lake area (ha)	Elevation (m, asl)	Mean depth (m)	TDS (mg / l)	Conductivity (ms /cm)	Spawning stream	Stream Length (km)[a]	Stream width (m)
Ethel	54° 32'	110° 21'	490	560	6.6	163	300	Marie Creek	4.4	55
Fawcett	55° 17'	113° 54'	3450	620	n/a	n/a	n/a	Mink River	3.3	60
Iosegun	54° 28'	116° 50'	1340	800	4.1	79	139	Fox River	1.9	30
Lesser Slave	55° 25'	115° 25'	116000	580	11.4	103	201	Heart River	5.4	100
Moose	54° 15'	110° 55'	4080	530	5.6	389	657	Thinlake River	4.0	70
Pigeon	53° 01'	114° 02'	10360	850	6.2	155	283	Tide Creek	3.0	20
Sturgeon	56° 06'	117° 29'	4850	720	5.4	78	158	Goose River	1.4	30
Wolf	54° 42'	110° 57'	3150	605	9.2	156	300	Wolf Creek	0.8	30

[a] stream length from known walleye spawning area to stream mouth

Table 6. Abundance of walleyes and shiners (*Notropis hudsonius* and *N. atherinoides*) at study lakes in Alberta. Walleye abundance determined from summer-season creel surveys during 1995 to 1997. Shiner abundance determined from seine hauls conducted during May and June, 1996 and 1997. Walleye catch per unit effort (CPUE) is the total number of fish caught / total hours fished. Shiner CPUE is total number of shiners caught / total area seined. Confidence limits of shiner CPUE are estimated from bootstrapped distributions of daily mean catches. Status of walleye fishery classified according to Berry (1995b) and Alberta Guide to Sportfishing (1996).

Year	Lake	Walleye Fishery Status	Walleye Angling CPUE (walleyes/angling-h)	Shiner CPUE (shiners/m^2)	Shiner 95% CI	Sample Size (Days, seine hauls)	Area seined (m^2)
1996	Iosegun	Stable	1.40	0.59	0.32-0.89	10 (80)	2940
1996	Sturgeon	Vulnerable	0.42	1.47	0.38-2.80	9 (72)	2520
1996	Pigeon	Collapsed	0.01	3.20	2.62-3.88	8 (62)	3075
1996	Wolf	Collapsed	0.02	3.75	1.50-6.20	10 (80)	4000
1997	Lesser Slave	Stable	1.10	0.08	0.05-0.10	15 (169)	8450
1997	Fawcett	Stable	1.39	0.03	0.02-0.03	10 (80)	4000
1997	Moose	Collapsed	0.21	0.43	0.13-0.76	16 (178)	9660
1997	Ethel	Collapsed	0.07	0.27	0.11-0.47	15 (178)	8870

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Thesis Synthesis and Conclusion

Why did Fisheries Management Fail in Alberta?

Ultimately, Alberta's walleye fisheries collapsed because unrestricted fishing pressure was exerted on low-productivity stocks. In a proximate sense, overfishing resulted in low fish abundance, initiating three depensatory mechanisms (i.e., illegal harvest, perceived hyperstability, and loss of cultivation effects) that contributed to the failure of management in preventing declines and collapses. Severe restrictions on fish harvest effected a partial recovery of some stocks, but their continual recovery or maintenance is unlikely using current management strategies. In spite of empirical evidence of these failures, fisheries managers in Alberta maintained strict adherence to traditional management tools (TMT) such as bag and size limits. For example, during province-wide public meetings held to determine regulations for walleye recovery (1994–1995), the only regulatory options allowed to be discussed were bag and size limits, gear restrictions, and seasons. Participants were told that strategies that restricted fishing effort were "not on the table." Recent proposals to restrict fishing effort have all failed to gain public or senior bureaucratic support.

To understand the role that fisheries management played in the collapse of the walleye fisheries, it is important to understand why managers adhered to TMT and refused to control fishing effort. Initially, the widespread decline of Alberta's walleye fisheries was reported to senior fisheries managers in 1986. During the next decade, numerous government fisheries management committees uniformly failed to achieve consensus on the status of Alberta's walleye fisheries and promoted only minor changes in bag and size limits. I believe that this was a logical response to the basic conflict of precautionary management: having to balance the typical uncertainty of stock status with the universal certainty of the social costs associated with restricting fishing (Weeks and Parker 2002). This conflict is formalized in the main policy goals of Alberta's Fisheries Management Division (Fisheries Management Division 1997). The

Division's mission statement, "To sustain fish populations at the carrying capacity of their habitats," will be in clear conflict with their operational goal of "providing open-access fisheries," because of Alberta's normally low-productivity, high-effort fisheries. These conflicting goals are similar to those of fisheries management agencies in most jurisdictions and are an attempt to balance conservation with human use of resources. Conflict arises, however, when because attempts to reach one goal concomitantly reduce the ability to reach the other. For example, if a new cottage subdivision increases angler use at a previously heavily fished lake, managers may want to impose additional harvest restrictions to prevent overfishing. Fisheries managers know that this would unquestionably result in complaints from current lake users about the loss of traditional opportunities, complaints from new developers about the decreased attractiveness of the lake to potential clients, and unwelcome scrutiny by senior managers and politicians. Countering these definite negative consequences are the uncertainties associated with fish conservation. Is the stock overfished? Will additional pressure degrade the stock status? Will the proposed regulations prevent degradation? The answers to these questions require lengthy (and expensive) field studies and will always have some degree of uncertainty. Managers are, therefore, asking for immediate social payment (i.e., loss of rights and opportunities) to prevent something that may not happen and may not be preventable. Under these circumstances, biological uncertainties promote reluctance in decision-making.

In trying to manage Alberta's walleye populations, biologists were faced with decisions that balanced immediate social costs with uncertain biological needs and benefits. The source of uncertainty, however, was not from imprecise or inaccurate data. During the decade of walleye debates (1986–1996), data presented to management committees (e.g., CPUE, angler effort, and walleye age and growth parameters) were very precise and were collected during field studies specifically designed to reduce variance and verify the accuracy of estimated parameters. The source of uncertainty was in the interpretation of this precise and accurate data. Is this low CPUE normal or unusual? Is this level of fishing effort too high? Do walleye in this lake ever get old? A common response from managers was that these parameters were stable, and the fishery had always been like this. In spite of these fisheries typically having been exploited for over a century, most managers only considered the changes that had occurred during their careers (20–30 years). Earlier data or anecdotes were usually considered outdated and unreliable. In this clear example of Pauly's shifting baseline syndrome (Pauly 1995; Pitcher 2001), decisions to restrict the harvest were avoided because the certainty of negative social consequences outweighed the uncertainty in stock status.

Curing Pauly's shifting baseline syndrome and reducing stock status uncertainty requires the adoption of larger scales of perspective for data interpretation, either in space or time. In Alberta, the existing reference scale (i.e., data from lake-specific studies and current managers' careers) was too short. Low-productivity fisheries had most likely declined within a few years of initial exploitation, and managers only had knowledge of and data from periods that were decades beyond the beginning of historical fisheries. Data from remote, unexploited populations could have provided a spatial reference scale, but this was deemed a very low priority when debates were about potentially collapsed, local fisheries. If Lake X was believed to be in trouble, biologists could get funding to study Lake X, but not untroubled, remote Lake Y. Instead, the solution was to continue studies on a local scale (e.g., is this fishery declining, starting from this point in time?), even though this scale could not provide the necessary answers. In hindsight, these fisheries had already declined. Managers needed the reference scale from the entire range of populations and fisheries responses.

Fisheries managers gained some degree of the necessary perspective regarding the status of the walleye fisheries in a novel manner. After a decade of failure in reaching consensus concerning fisheries status and regulations, fisheries management decisions were opened to discussion in public forums. A series of 17 townhall-style meetings were held throughout Alberta during 1994 and 1995. Local participants were selected from specific groups (including anglers, tackle-store owners, commercial fishermen, First Nations fishermen, and local naturalists). Data on the status of the walleye fisheries were presented to the groups, with relatively little interpretation being given. This allowed a broad group of people, with equally broad perspective, to assess walleye stock status. Consensus on the serious nature of the stock status was quickly achieved, and participants uniformly recommended severe harvest restrictions (i.e., catch-and-release and large minimum length limits). Because these recommendations came from the public, the social costs of decisions, from the fisheries managers' point of view, were virtually eliminated. Government approval of the publicly recommended regulation changes was immediate. These public meetings were successful because they resolved the conflict between the uncertainties involved in conservation versus the certainties of social costs. Conservation uncertainties were reduced because the increased perspective of participants lessened Pauly's syndrome, and the certain social costs were minimized (i.e., complaints and scrutiny were easily handled by biologists by saying that the public had recommended the regulations).

Growth-overfished walleye populations quickly increased in abundance following harvest reductions, providing additional perspective on the capacity of Alberta's lakes to produce higher-quality fisheries. Because of this increased perspective, anglers and managers are unlikely to accept poor walleye fisheries again, but they do not yet regard higher-quality fisheries as normal.

These two events (the public meetings and the partial recovery of some fisheries) were instrumental in broadening our understanding of the potential of low-productivity fisheries. As such, they were critical first steps in solving Pauly's shifting baseline syndrome and reducing uncertainty in data interpretation. The goal, however, is to gain full perspective and acceptance of the potential of Alberta's walleye populations. This addresses the primary task of fisheries stock assessment: to inform decision-makers of the present status of a fishery *in relation to its potential status,* and the likely consequences of management actions (Hilborn and Walters 1992; Healy 1997; Hutchings et al. 1997). With any low-productivity, high-effort fisheries, traditional management strategies and tools will fail to maintain high-quality fisheries or enhance recovering fisheries and will consequently fail to provide any critical examples or informed perspective of potential fishery status. To succeed in stock assessment under these conditions, I propose a new management model, incorporating both direct and indirect harvest controls and focussing on providing a broader understanding of the potential of low-productivity fisheries.

Model of Thresholds for Effective Management of Low-Productivity Fisheries

Typical northern fisheries (i.e., those with low biological productivity relative to potential fishing effort) can be viewed as existing in zones of stock status along a scale between the following parameters: high CPUE – low effort (i.e., unexploited) and low CPUE – high effort (i.e., collapsed) (Figure 1). Increased fishing effort, usually because of improved road access, causes the status of the fishery to decline. Two thresholds, one of decline and one of collapse, represent quantifiable points along this scale. Management actions that do not control fishing effort fail at either end of the scale. TMT would, falsely, appear effective only at the midpoint, where fishing effort is balanced with CPUE in maintaining the fisheries, and regulations are not necessary. To maintain high-quality fisheries and restore collapsed fisheries, harvest controls are required.

The parameters for each stock status zone are as follows:

High-Quality Fisheries

Description of fishery.—Fish population is relatively unexploited and shows slow growth, late maturity, low mortality, and numerous age-classes. Fishing quality is high, with high CPUE and large fish.

Effect of traditional management tools.—At low fishing effort (e.g., no road access), regulations are unnecessary to maintain these fisheries. At high effort (e.g., new road access), bag and size limits, and catch-and-release regulations fail to control harvest because of the large catch (high effort and high CPUE) and associated by-catch mortality.

Management requirements.—Harvest (including by-catch) must be kept below the annual total allowable catch (TAC), while maintaining the high CPUE and catch of large fish that define these fisheries. Direct control of fishing effort (including that which affects by-catch) is required. A limited number of time-specific licences (e.g., one-day permits) would be issued based on estimated productivity, CPUE, by-catch mortality, and harvest options.

Mediocre Fisheries

Description of fishery.—Fish population is growth overfished. Recruitment is maintained, but heavy fishing mortality reduces older age-classes. Characteristics include moderate growth, early maturity, high adult mortality, and few age-classes. Fishing quality is mediocre, with low CPUE and small fish.

Effect of traditional management tools.—At moderate fishing effort, regulations are unnecessary to maintain these fisheries. Harvest and by-catch are restricted by the low CPUE. Bag limits do not limit the harvest because few anglers catch the bag limit. If fish mature at smaller sizes (i.e., those not vulnerable to fishing), the spawning population (and the condition of growth overfishing) will be maintained without the use of size limit regulations. If fish mature at larger sizes (i.e., those vulnerable to fishing), increased fishing effort will eventually result in recruitment overfishing. Size limits will artificially increase the size of vulnerability and prevent recruitment overfishing. Strategies using TMT, however, will not allow the recovery of these fisheries. Increases in fish abundance (through management actions or stochastic recruitment) will be counteracted by the following progression: increased CPUE, increased attractiveness to anglers, increased effort, increased harvest and by-catch, and ultimately, decreased fish abundance. Decreases in fish abundance (through increased fishing effort or stochastic recruitment) may result in recruitment overfishing that is undetected by managers because of perceived hyperstability in reported catches.

Management requirements.—To restore these fisheries to their former high-quality status, increases in fish abundance must be protected from increased fishing effort. Very large size limits or total catch-and-release regulations will make the fisheries temporarily unattractive to anglers until high-quality status is reached.

Collapsed Fisheries

Description of fishery.—Fish population is recruitment overfished. Abundance of fish in each age-class is very low. Characteristics include very low recruitment, fast growth, and early maturity. Fishing quality is poor, with very low CPUE, which is falsely reported to be higher than in reality. Poor recruitment results in low numbers of young fish, causing the average size of the few fish in anglers' catches to be large. Because of incorrect perceptions of higher CPUE and stories of large fish, anglers continue to be attracted to these fisheries.

Effect of traditional management tools.—Regulations based on TMT generally fail to restore the fishery. Size limits fail because of high illegal harvest. Bag limits fail because few anglers catch more than one fish. Of equal importance, management responses are strongly hindered by an uncertainty in the fishery status as anglers report exaggerated catch rates and large fish.

Management requirements.—If managers can break the impasse of uncertainty and impose severe regulations (e.g., very large minimum size limits or catch-and-release regulations), the attractiveness of the fishery may decline. The resulting decrease in fishing effort may allow recovery, assuming that depensatory cultivation effects are also restored. Recovery will ultimately depend on stochastic recruitment and long-term survival of strong year-classes. Managers, however, will then be faced with the scenario of conflicting interpretations of overall stock status, evidence of strong recruitment, and the underlying need to maintain stringent harvest controls. Under these conditions, public support for severe harvest restrictions will be very difficult to maintain.

Using this conceptual model, consider the typical scenario of a new road providing anglers with access to a formerly unfished lake. Very high CPUE and large fish attract many anglers. Bag limits fail to restrict the harvest because of the large number of anglers all catching the limit. Size limits fail to restrict the legal harvest because most anglers catch fish larger than the size limit, and they fail to restrict the by-catch of smaller fish because of the high total catch. At such high effort and CPUE, the low by-catch mortality (in terms of percentage) of released fish will be multiplied by the high total catch, resulting in large numbers of fish being killed. Consequently, fish decline in abundance and size, but effort remains high because of anglers' memories and perceptions of great fishing. If biological productivity is strongly outbalanced by fishing effort (as may occur at a small lake), the fishery will quickly collapse. The fish population may be extirpated in extreme cases, perhaps because heavy fishing effort is maintained by way of an alternate species, or because of severe trophic cascade effects. The fish may remain as a remnant population, however, neither attracting anglers nor having effective ecological functions. Management actions relying on TMT will have, in the worst case, no effect in slowing the decline in stock status from high-quality to collapsed. At best, TMT may stabilize the fishery in the zone of mediocrity until a chance event such as a year-class failure or increased fishing pressure results in the capture of the fishery by depensatory responses. Stochastic events that improve the fishery, such as an unusually strong year-class production or a drop in fishing effort, may temporarily push it into the high-quality zone, but TMT will again fail to hold it there. In this model, fluctuations in either fish or angler numbers will eventually ratchet the fishery into collapse.

Definition of thresholds

The thresholds between the zones of stock status may be quantitatively defined. The threshold of decline occurs when catch (i.e., effort x CPUE) exceeds biological production (Figure 2). Consider the hypothetical example of a 300 ha lake with an unexploited walleye population. Assume that sustainable production is 0.5 kg/ha, and catchable fish are large (average weight = 2 kg). The TAC is, therefore, 75 walleye. CPUE is initially high, at 2 fish/h, with a daily trip length of 4 h/angler. With complete catch-and-release regulations (assuming

10% by-catch mortality caused by hooking and illegal harvest), the TAC will be taken in 94 angler-trips. If a bag limit of one fish is allowed, the TAC will be taken in 42 angler-trips. With a summer-season fishery lasting 90 days, this effort constitutes one trip every two days. In this scenario, the threshold of decline is defined by angler effort (i.e., one angler-trip every one to two days, depending on the regulation). Creel survey crews at fisheries with such low effort may easily fail to interview any anglers, yet the TAC will have been exceeded. At lower-productivity lake trout fisheries (assuming a sustainable production of 0.2 kg/ha), the TAC at a similar 300 ha lake may be 30 fish, with a threshold of 17 angler-trips (with a one-fish bag limit). Maximum allowable effort is one angler-trip every five days during the summer season, and only one angler-trip every 21 days over the entire year. Limiting fishing effort is clearly necessary to prevent the fishery from declining into mediocre status.

The threshold of collapse is exceeded when depensatory responses are initiated on a mediocre fishery. In Alberta, the depensatory response of illegal harvest increased sharply below a catch rate of 0.2 fish/h (Chapter 2). This is the same catch rate as at the inflection point on the curve of reported versus estimated CPUE (Chapter 3), reflecting the maximum degree of perceived hyperstability. Depensatory cultivation effects were lost at walleye densities below 3 fish/ha, corresponding to a catch rate below 0.1 fish/h (Chapter 5). For walleye in Alberta, the threshold of collapse may be initiated at catch rates between 0.2 and 0.1 fish/h. This threshold would most likely vary between species and ecosystems. If a species had greater or lesser desirability to anglers, illegal harvest and exaggeration could occur at higher or lower catch rates, respectively. Similarly, ecosystems with more or fewer predatory species may lose cultivation effects at lower or higher densities, respectively.

Conclusions

Alberta's low-productivity walleye fisheries declined and collapsed because uncertainty in data interpretation hindered decisions to restrict excessive harvests. Consequently, fisheries declined to levels at which depensatory mechanisms promoted collapse. Extensive public involvement in data interpretation and decision-making expanded the perspective of walleye fishery status, reduced uncertainty, and allowed harvest restrictions to be implemented. Partial recovery of growth-overfished walleye populations has further expanded this perspective, but data from unexploited walleye fisheries are needed to demonstrate the potential of these fisheries. I propose a management model that advocates strongly protecting (using fishing-effort controls) recovering and lightly exploited fisheries. Initially, this strategy may appear to be counterintuitive, but it is ultimately necessary to demonstrate the full range of fishery potential and reduce uncertainty in future decisions concerning low-productivity fisheries.

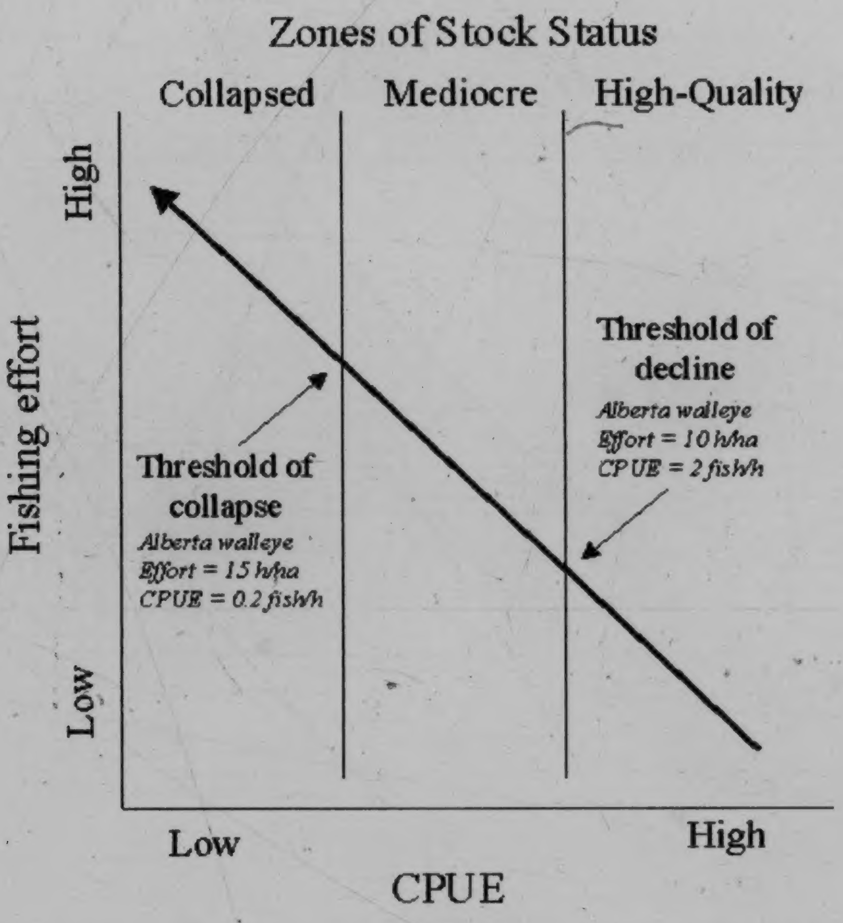
Zones of Stock Status
Collapsed
Mediocre
High-Quality
Fishing effort
High
Low
Threshold of decline
Alberta walleye
Effort = 10 h/ha
CPUE = 2 fish/h
Threshold of collapse
Alberta walleye
Effort = 15 h/ha
CPUE = 0.2 fish/h
Low
High
CPUE

Figure 1. Conceptual model of thresholds for management of low-productivity fisheries. Fisheries may exist in one of three zones: high-quality, mediocre, or collapsed. As fishing effort on unexploited, high-quality fisheries increases, management tools that indirectly control harvest (e.g., bag and size limits, gear restrictions, and seasons) will fail to prevent fisheries from passing the critical thresholds and will allow them to decline and eventually collapse. Thresholds for Alberta walleye fisheries are shown in italics.

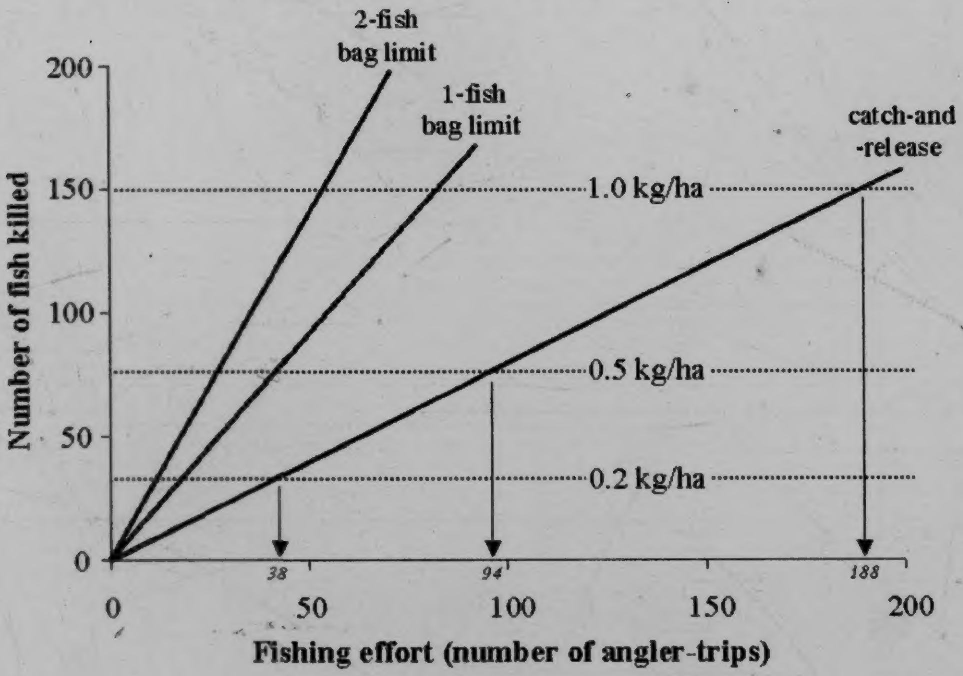

Figure 2. Fishing effort thresholds of decline in high-quality, low-productivity fisheries. Diagonal lines represent the number of fish killed versus fishing effort using one of three regulation options (two-fish bag limit, one-fish bag limit, and catch-and-release). Dashed lines represent the total allowable catch at three biological productivity levels (0.2 kg/ha, 0.5 kg/ha, and 1 kg/ha, simulating low-productivity lake trout, walleye, and northern pike populations, respectively). The intersection of diagonal and dashed lines (e.g., arrows) represents thresholds of maximum allowable fishing effort for each regulation option and productivity level. Model parameters: 300 ha lake, 2-kg mean fish weight, CPUE of 2 fish/h, angler-trip of 4 h, by-catch mortality of 10%. In the example illustrated (using catch-and-release regulations), the TAC would be taken in 38 angler-trips for lake trout, 94 angler-trips for walleye, and 188 angler-trips for northern pike.

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